FIBER OPTIC SENSORS FOR INFRASTRUCTURE APPLICATIONS

Final Report

SPR 374

RESEARCH

Oregon Department of Transportation

FIBER OPTIC SENSORS FOR INFRASTRUCTURE APPLICATIONS

Final Report

SPR 374

by

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Fiber optic sensor technology offers the possibility of implementing "nervous systems" for infrastructure elements that allow high performance, cost effective health and damage assessment systems to be achieved. This is possible, largely due to synergistic developments in the fiber optic telecommunication and optoelectronics fields, where industries with multi-billion dollar research and development budgets exist. Now, essential components are becoming available with prices and performance that are improving dramatically on an annual basis. This report is an introduction to fiber optics, fiber optic sensor technology and some of the applications that make this field, which is still in its early infancy, one of the most promising new developments in infrastructure systems.</td></tr>
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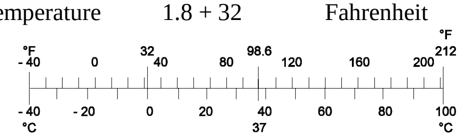
SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	Millimeters	Mm
ft	feet	0.305	Meters	M
yd	yards	0.914	Meters	M
mi	miles	1.61	Kilometers	Km
		AREA		
in^2	square inches	645.2	Millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	Hectares	Ha
mi^2	square miles	2.59	kilometers squared	km^2
		VOLUME		
fl oz	fluid ounces	29.57	Milliliters	ML
gal	gallons	3.785	Liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
		MASS		
oz	ounces	28.35	Grams	G
lb	pounds	0.454	Kilograms	Kg
T	short tons (2000 lb)	0.907	Megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celsius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
Mm	millimeters	0.039	inches	in
M	meters	3.28	feet	ft
M	meters	1.09	yards	yd
Km	kilometers	0.621	miles	mi
		AREA		
Mm^2	millimeters squared	0.0016	square inches	in^2
M^2	meters squared	10.764	square feet	ft^2
Ha	hectares	2.47	acres	ac
Km^2	kilometers squared	0.386	square miles	mi^2
		VOLUME		
ML	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
M^3	meters cubed	35.315	cubic feet	ft^3
M^3	meters cubed	1.308	cubic yards	yd^3
		MASS		
G	grams	0.035	ounces	oz
Kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8 + 32	Fahrenheit	°F



* SI is the symbol for the International System of Measurement (4-7-94 jbp)

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DISCLAIMER

FIBER OPTIC SENSORS FOR INFRASTRUCTURE APPLICATIONS

TABLE OF CONTENTS

FIBER OPTIC SENSORS GLOSSARY XI
1.0 OVERVIEW 1
1.1 FOREWORD 1
1.2 FIBER OPTIC SENSOR TECHNOLOGY FOR INFRASTRUCTURE SYSTEMS 1
1.2.1 Key Features 1
1.2.2 Categories 2
1.3 SELECTED APPLICATION EXAMPLES 3
1.3.1 Concrete Cure Monitoring 4
1.3.2 Retaining Wall Anchor 5
1.3.3 Tunnels 6
1.3.4 Torque Measurements 6
1.3.5 Corrosion Sensors 6
1.3.6 Suspension Bridges 7
1.3.7 Drawbridges 8
1.3.8 Truss Monitoring 9
1.3.9 Acoustic Sensors 10
1.3.10 Soil Measurement 10
1.3.11 Traffic Control 11
1.3.12 Traffic Monitoring 11
1.3.13 Road Conditions 12
1.4 WHERE TO FIND ADDITIONAL INFORMATION IN THIS REPORT 12
1.5 SUMMARY 13
2.0 INTRODUCTION TO FIBER OPTIC BASICS 15
2.1 BASIC PHYSICS OF LIGHT 15
2.1.1 Photons 15
2.1.2 Light models 19
2.2 OPTICAL FIBERS 21
2.2.1 Index of Refraction 21
2.2.2 Concepts of Guided Light 28
3.0 INTRODUCTION TO FIBER OPTIC SENSORS 53
3.1 BASIC CONCEPTS AND INTENSITY BASED FIBER OPTIC SENSORS 54
3.2 SPECTRALLY BASED FIBER OPTIC SENSORS 62
3.3 INTERFEROMETRIC FIBER OPTIC SENSORS 68
3.3.1 The Sagnac Interferometer 68
3.3.2 The Mach-Zehnder and Michelson Interferometers 72
3.4 MULTIPLEXING AND DISTRIBUTED SENSING 78
3.5 APPLICATIONS 82

4.0 GENERAL INTRODUCTION TO FIBER OPTIC SENSORS FOR TRANSPORTATION INFRASTRUCTURE APPLICATIONS 87
4.1 MICROBEND SENSORS 87
4.1.1 Basic Operation 87
4.1.2 Applications 88
4.1.3 Advantages/Disadvantages 89
4.2 ETALON SENSORS 90
4.2.1 Basic Operation 90
4.2.2 Applications 91
4.2.3 Advantages/Disadvantages 91
4.3 GRATING SENSORS 91
4.3.1 Basic Operation 91
4.3.2 Applications 94
4.3.3 Advantages/Disadvantages 95
4.4 RESPONSE OF OPTICAL FIBERS 95
4.5 INTERFEROMETRIC SENSORS 96
4.5.1 Basic Uses 96
4.5.2 Advantages of Interferometric Fiber Sensors 105
5.0 SYNTHESIS OF SENSOR APPLICATIONS 107
5.1 MICROBEND SENSORS 107
5.1.1 Current Research 107
5.1.2 Field Applications 111
5.1.3 Installation Details 112
5.1.4 Component Cost and Availability 112
5.1.5 Future Development 113
5.2 ETALON SENSORS 113
5.2.1 Current Research 113
5.2.2 Field Applications 113
5.2.3 Installation Details 114
5.2.4 Component Cost and Availability 114
5.2.5 Future Development 114
5.3 GRATING SENSORS 114
5.3.1 Current Research 114
5.3.2 Field Applications 115
5.3.3 Installation Details 115
5.3.4 Component Cost and Availability 115
5.3.5 Future Development 116
5.4 INTERFEROMETRIC SENSORS 117
5.4.1 Current Research 117
5.4.2 Field Applications 117
5.4.3 Installation Details 117
5.4.4 Component Cost and Availability 117
5.4.5 Future Development 118
5.5 OTHER FIBER SENSORS USED FOR CIVIL STRUCTURES 118
5.6 SMART STRUCTURES 118
5.7 SUMMARY 118

6.0 REFERENCES 119

APPENDICES

APPENDIX A: INSTALLATION TECHNIQUES FOR FIBER OPTIC SENSORS
APPENDIX B: PROCEDURE FOR CLEANING CONNECTORS

LIST OF TABLES

Table 1.1: Report Contents 12
Table 1.2: Summary of Fiber Optic Sensors 14
Table 2.1: Indices of Refraction of Various Materials at .589 Microns (*Halliday*) 22

LIST OF PHOTOS/FIGURES

Figure 1.1: Embedded temperature sensor to measure curing of thick concrete pad 4
Figure 1.2: Strain sensors on retaining wall anchor 5
Figure 1.3: System of strain sensors to monitor condition of tunnels 6
Figure 1.4: Strain sensors on suspension bridge 7
Figure 1.5: Strain sensors embedded in supports to measure the balance of a drawbridge 8
Figure 1.6: Strain sensor monitoring truss reinforced with composite brace 9
Figure 1.7: Acoustic sensor to detect anomalies in roads, bridges, railway tracks, etc. 10
Figure 1.8: Strain sensors for traffic control 11
Figure 1.9: Strain sensors for speed and weight measurements 11
Figure 2.1: Electromagnetic spectrum 16
Figure 2.2: Unpolarized light incident on ideal linear polarizer 17
Figure 2.3: Unpolarized light incident on two crossed polarizers 18
Figure 2.4: Electric field of light as transverse wave (shown vertically polarized) 18
Figure 2.5: Rays of light from various sources 20
Figure 2.6: Plane-wavefronts 20
Figure 2.7: Snell's law for lower index to higher index 22
Figure 2.8: Air to water interface 23
Figure 2.9: Angle of reflection 24
Figure 2.10: Snell's law for glass to air 26
Figure 2.11: Total internal reflection for glass to air 27
Figure 2.12: Basic fiber structure 29
Figure 2.13: Snell's law example for fiber (Ni/Nt = 1.003) 30
Figure 2.14: Numerical aperture 32
Figure 2.15: Rays representing modes in step index fiber 34
Figure 2.16: Overfill of numerical aperture 35
Figure 2.17: Cladding modes 36
Figure 2.18: Mode paths through step-index fiber 36
Figure 2.19: Pulse spreading from modes 37
Figure 2.20: Examples of polychromatic spectra 39
Figure 2.21: Material and waveguide dispersion for glass fiber 40
Figure 2.22: Profile of index of refraction for graded-index fiber 40
Figure 2.23: Model depicting layers of different indices of refraction for graded-index fiber 41
Figure 2.24: Modes propagating in graded-index fiber 41
Figure 2.25: Attenuation vs. wavelength (single mode, glass fiber) 43
Figure 2.26: Wavelength division multiplexing 47

Figure 3.1: Extrinsic fiber optic sensors consist of optical fibers that lead up to and out of a "black box" that modulates the light beam passing through it in response to an environmental effect. 54
Figure 3.2: Intrinsic fiber optic sensors rely on the light beam propagating through the optical fiber being modulated by the environmental effect either directly or through environmentally induced optical path length changes in the fiber itself. 54
Figure 3.3: Closure and vibration fiber optic sensors based on numerical aperture can be used to support door closure indicators and measure levels of vibration in machinery. 55
Figure 3.4: Numerical aperture fiber sensor based on a flexible mirror can be used to measure small vibrations and displacements. 55
Figure 3.5: Fiber optic translation sensor based on numerical aperture uses the ratio of the output on the detectors to determine the position of the input fiber. 56
Figure 3.6: Fiber optic rotary position sensor based on reflectance used to measure rotational position of the shaft via the amount of light reflected from dark and light patches. 56
Figure 3.7: Linear position sensor using wavelength division multiplexing decodes position by measuring the presence or absence of reflective patch at each fiber position as the card slides by via independent wavelength separated detectors. 57
Figure 3.8: Linear position sensor using time division multiplexing measure decodes card position via a digital stream of on’s and off’s dictated by the presence or absence of a reflective patch. 57
Figure 3.9: Fiber sensor using critical angle properties of a fiber for pressure/index of refraction measurement via measurements of the light reflected back into the fiber. 58
Figure 3.10: Liquid level sensor based on total internal reflection detects the presence or absence of liquid by the presence or absence of a return light signal. 58
Figure 3.11: Evanescence based fiber optic sensors rely on the cross coupling of light between two closely spaced fiber optic cores. Variations in this distance due to temperature, pressure or strain offer environmental sensing capabilities. 59
Figure 3.12: Microbend fiber sensors are configured so that an environmental effect results in an increase or decrease in loss through the transducer due to light loss resulting from small bends in the fiber. 60
Figure 3.13: Grating based fiber intensity sensors measure vibration or acceleration via a highly sensitive shutter effect. 60
Figure 3.14: Dynamic range limitations of the grating based sensor of Figure 3.13 are due to smaller grating spacing increasing sensitivity at the expense of range. 61
Figure 3.15: Dual grating mask with regions 90 degrees out of phase to support quadrature detection which allows grating based sensors to track through multiple lines. 61
Figure 3.16: Diagram illustrating quadrature detection method that allows one area of maximum sensitivity while the other reaches a minimum and vice versa, allowing uniform sensitivity over a wide dynamic range. 62
Figure 3.17: Blackbody fiber optic sensors allow the measurement of temperature at a hot spot and are most effective at temperatures of higher than 300 degrees C. 62
Figure 3.18: Blackbody radiation curves provide unique signatures for each temperature. 63
Figure 3.19: Fiber optic sensor based on variable absorption of materials such as GaAs allows the measurement of temperature and pressure. 63
Figure 3.20: Fluorescent fiber optic sensor probe configurations can be used to support the measurement of physical parameters as well as the presence or absence of chemical species. These probes may be configured to be single ended or multipoint by using side etch techniques and attaching the fluorescent material to the fiber. 64
Figure 3.21: Fabrication of a fiber grating sensor can be accomplished by imaging to short wavelength laser beams through the side of the optical fiber to form an interference pattern. The bright and dark fringes that are imaged on the core of the optical fiber induce an index of refraction variation resulting in a grating along the fiber core. 65
Figure 3.22: Fiber grating demodulation systems require very high-resolution spectral measurements. One way to accomplish this is to beat the spectrum of light reflected by the fiber grating against the light transmission characteristics of a reference grating. 66
F igure 3.23: Intrinsic fiber etalons are formed by in line reflective mirrors that can be embedded into the optical fiber. Extrinsic fiber etalons are formed by two mirrored fiber ends in a capillary

tube. A fiber etalon based spectral filter or demodulator is formed by two reflective fiber ends that have a variable spacing. 66
Figure 3.24: Diagram illustrating the transmission characteristics of a fiber etalon as a function of finesse, which increases with mirror reflectivity. 67
Figure 3.25: Hybrid etalon based fiber optic sensors often consist of micromachined cavities that are placed on the end of optical fibers and can be configured so that sensitivity to one environmental effect is optimized. 67
Figure 3.26: Open loop fiber optic gyro is the simplest and lowest cost rotation sensor. They are widely used in commercial applications where their dynamic range and linearity limitations are not constraining. 69
Figure 3.27: An open loop fiber optic gyro has predominantly even order harmonics in the absence of rotation. Upon rotation, the open loop fiber optic gyro has odd harmonic output whose amplitude indicates the magnitude of the rotation rate and phase indicates direction. 70
Figure 3.28: A typical open loop fiber optic gyro output obtained by measuring one of the odd harmonic output components amplitude and phase, results in a sinusoidal output that has a region of good linearity centered about the zero rotation point. 70
Figure 3.29: Closed loop fiber optic gyros use an artificially induced nonreciprocal phase between counterpropagating light beams to counterbalance rotationally induced phase shifts. These fiber gyros have the wide dynamic range and high linearity needed to support stringent navigation requirements. 71
Figure 3.30: Distributed fiber optic acoustic sensor based on interlaced Sagnac loops allows the detection of the location and the measurement of the amplitude along a length of optical fiber that may be many kilometers long. 72
Figure 3.31: Flexible geometries of interferometric fiber optic sensors' transducers are one of the features of fiber sensors that are attractive to designers configuring special purpose sensors. 72
Figure 3.32: The basic elements of the fiber optic Mach-Zehnder interferometer are a light source module to split a light beam into two paths, a transducer used to cause an environmentally dependent differential optical path length between the two light beams, and a demodulator that measures the resulting path length difference between the two light beams. 73
Figure 3.33: In the absence of compensating demodulation methods, the sensitivity of the Mach-Zehnder varies with the relative phase between the two light beams. It falls to low levels when the light beams are completely in or out of phase. 74
Figure 3.34: Quadrature demodulation avoids signal fading problems. The method shown here expands the two beams into an interference pattern that is imaged onto a split detector. 74
Figure 3.35: Quadrature demodulation electronics take the sinusoidal outputs from the split detector and convert them via cross multiplication and differentiation into an output that can be integrated to form the direct phase difference. 75
Figure 3.36: The phase generated carrier technique allows quadrature detection via monitoring even and odd harmonics induced by a sinusoidally frequency modulated light source used in combination with a length offset Mach-Zehnder interferometer to generate a modulated phase output whose first and second harmonics correspond to sine and cosine outputs. 76
Figure 3.37: The fiber optic Michelson interferometer consists of two mirrored fiber ends and can utilize many of the demodulation methods and techniques associated with the Mach-Zehnder. 76
Figure 3.38: Coatings can be used to optimize the sensitivity of fiber sensors. An example would be to use soft and hard coatings over an optical fiber to minimize the acoustic mismatch between acoustic pressure waves in water and the glass optical fiber. 77
Figure 3.39: Optical fiber bonded to hollow mandrills and strips of environmentally sensitive material are common methods used to mechanically amplify environmental signals for detection by fiber sensors. 77
Figure 3.40: Differential methods are used to amplify environmental signals. In this case, a seismic/vibration sensor consists of a mass placed between two fiber coils and encased in a fixed housing. 78
Figure 3.41: Time division multiplexing methods can be used in combination with microbend sensitive optical fiber to locate the position of stress along a pipeline. 78
Figure 3.42: Frequency division multiplexing can be used to tag a series of fiber sensors, as in this case the Mach-Zehnder interferometers are shown with a carrier frequency on which the output signal ride. 79

Figure 3.43: Wavelength division multiplexing are often very energy efficient. A series of fiber sensors are multiplexed by being arranged to reflect in a particular spectral band that is split via a dispersive element onto separate detectors. ... 80
Figure 3.44: A low coherence light source is used to multiplex two Mach-Zehnder interferometers by using offset lengths and counterbalancing interferometers. ... 80
Figure 3.45: Polarization multiplexing is used to support two fiber sensors that access the cross polarization states of polarization preserving optical fiber. ... 81
Figure 3.46: Spatial multiplexing of four fiber optic sensors may be accomplished by operating two light sources with different carrier frequencies and cross coupling the sensor outputs onto two output fibers. ... 81
Figure 3.47: Extensions of spatial multiplexing the JK sensors can be accomplished by operating J light sources at J different frequencies and cross coupling to K output fibers. ... 82
Figure 3.48: Fiber optic smart structure systems consist of optical fiber sensors embedded or attached to parts sensing environmental effects that are multiplexed and directed down. The effects are then sent through an optical fiber to an optical/electronic signal processor that in turn feeds the information to a control system that may or may not act on the information via a fiber link to an actuator. ... 83
Figure 3.49: Smart manufacturing systems offer the prospect of monitoring key parameters of parts as they are being made, which increases yield and lowers overall costs. ... 84
Figure 3.50: A modular architecture for a large smart structure system would consist of strings of fiber sensors accessible via an optical switch and demodulator system that could select key sensors in each string. The information would then be formatted and transmitted after conditioning to a vehicle health management bus. ... 85
Figure 3.51: A typical vehicle health management bus for an avionics system would be the interface point for the fiber optic smart structure modules of Figure 3.50. ... 85
Figure 3.52: Fiber optic sensor networks to monitor the status of widely dispersed assets as buildings, bridges and dams could be used to augment fire, police and maintenance services. ... 86
Figure 4.1: Microbend and macrobend loss ... 87
Figure 4.2: “Figure 8” sensor for detecting large movements ... 89
Figure 4.3: The two mirror etalon ... 90
Figure 4.4: Three-axis strain and temperature sensor based on dual overwritten fiber gratings on polarization preserving fiber ... 93
Figure 4.5: Compliant mandrel fiber optic acoustic sensor ... 96
Figure 4.6: Bulk optic Mach-Zehnder interferometer ... 97
Figure 4.7: Fiber optic Mach-Zehnder interferometer ... 97
Figure 4.8: Bulk optic Michelson interferometer ... 98
Figure 4.9: Fiber optic Michelson interferometer ... 98
Figure 4.10: The Sagnac effect ... 100
Figure 4.11: Optical resonator ... 100
Figure 4.12: Open loop interferometer ... 101
Figure 4.13: Sagnac acoustic sensor ... 102
Figure 4.14: Effect of an acoustic wave, which has a wavelength that is large compared to the Sagnac coil on a Sagnac acoustic sensor ... 103
Figure 4.15: Two methods for shielding fiber to obtain optimum sensitivity ... 103
Figure 4.16: Time varying effect ... 104
Figure 5.1: Bend loss induced displacement sensor ... 107
Figure 5.2: Basic setup to support bend induced displacement sensor ... 108
Figure 5.3: Plot of the reasonably linear (~20mm) region of the displacement sensor ... 108
Figure 5.4: Output of the displacement sensor over a 400-mm range ... 109
Figure 5.5: Microbend sensitive fiber wound around a mandrel subject to load ... 109
Figure 5.6: Scheme for measuring transverse load using several microbend sensitive elements ... 110
Figure 5.7: Compression load test of the system in Figure 5.6 ... 110
Figure 5.8: Fiber optic strain sensor based on bending loss ... 111
Figure 5.9: Loading of a composite pipe using the sensor of Figure 5.8 ... 111
Figure 5.10: Composite pipe load tests using the sensor of Figure 5.8 ... 112
Figure 5.11: Fiber grating sensor demodulation system ... 116

FIBER OPTIC SENSORS GLOSSARY

A

absorption – The loss of some or all of the energy contained in an electromagnetic wave to the medium in which it is propagating. The lost energy is usually converted to heat.

acceptance angle – The maximum angle, measured from the optical fiber centerline to an incident light ray, within which the incident ray will be accepted for transmission by total internal reflection along the fiber. If the incident angle is greater then the acceptance angle, total internal reflection will not occur and the incident ray will be lost by leakage.

acousto-optics – The study of the relationships between acoustics and optics.

Angstrom (Å) – A unit of length equal to 10^{-1} nanometer (10^{-1} nm), 10^{-4} micron (10^{-4} μm), and 10^{-10} meter (10^{-10} m).

array – See sensor array.

attenuation – The decrease in power of a signal, or light wave, from interaction with the propagation medium. The decrease usually occurs as a result of absorption, reflection, diffusion, scattering, deflection, dispersion or resistance.

B

bandwidth – The range of frequencies that a device is capable of handling.

beam splitter – An optical device for dividing a light beam into two separated beams.

bend loss – See microbend loss.

birefringence – The separation of a light beam into two components to form two rays propagating at different velocities in the medium.

Bragg cell – An acousto-optic device that is capable of modulating light waves to produce an output light wave with an imposed frequency equal to the frequency of the input signal.

C

cable – A group of insulated conductors that are bound together, usually with a durable cable jacket.

cable jacket – The outer protective covering over insulated conductors that are bound together.

cladding – An optical transparent material over the core of the fiber optic cable, with a refractive index lower than that of the core, to provide total internal reflectance.

coherence length – The coherence time of a light beam multiplied by the velocity of the light. See coherence time.

coherence time – If t is the time a light beam becomes coherent, and $t + \Delta t$ is the time at which the light beam loses its coherent properties, Δt is the coherence time.

coherent light – Light which has predictable parameters at any point in time or space. For example, laser light.

conductor – A transparent medium that is capable of transmitting or conveying light waves by total internal reflection.

connector – A coupling device that permits a signal to pass from one optical fiber to another.

connector insertion loss – The power loss due to the insertion of a connector between two elements.

core – The primary light-conducting region of an optical fiber. The refractive index of the core is higher than its cladding, the condition necessary for total internal reflection.

coupler – A connector that is used interconnect two or more optical fibers.

coupler (3-dB) – A coupler that splits the optical energy in an optical waveguide into two equal parts and couples each part into a separate waveguide. The 3-dB coupler ideally distributes 50% of the input optical power to each of the output channels.

coupling – The connection between elements, whether physical or across a gap, where energy from one element is transferred to one or more other elements.

coupling loss – The power loss caused by the coupling.

coupling ratio – The ratio of the output power to the input power.

critical angle – When an incident light ray traveling in one medium strikes another medium whose index of refraction is greater, the incident light ray may be reflected or refracted. The critical angle, measured from the normal to the reflecting surface, is where total internal reflection begins. Total internal reflection continues for all angles greater than the critical angle.

critical radius – The radius of curvature of an optical fiber containing an axially propagated light wave at which microbend losses begin to occur.

D

data link – A communication link suitable for transmission of data. The data link does not include the data source and the data sink.

decibel (dB) – A gain or attenuation factor, measured as 10 times the log of a power ratio.

demodulation – The extraction of the original signal from the carrier. See modulation.

detector – A device that responds to a signal and reproduces the signal in a new form, usually in a form that is easier to process. See photo-detector.

diffraction – The bending of radio, sound, or light waves around an edge; typically aperture edges.

dispersion – Optical: the dependence of the refractive index, n, of a medium on the wavelength, λ.

i.e. dispersion = $\dfrac{dn}{d\lambda}$

Wavelength dependent time-of-flight of an optical signal resulting from the fact that the index of refraction of a fiber is wavelength dependent.

distortion – See waveguide delay distortion.

E

electromagnetic interference (EMI) – Interference caused in a circuit by radiation through coupling.

electro-optic device – A devices that converts electronic signals to optic signals or optic signals to electronic signals.

EMI – See electromagnetic interference.

evanescent wave – The wave radiating away from the fiber at sharp bends in the fiber where the radius of the bend is less than the critical radius.

F

Fabry Perot interferometer – A high resolution multiple beam interferometer especially sensitive to linear motion of the mirrors.

fiber – Any type of optic fiber.

fiber loss – Power loss in an optical fiber, usually expressed in dB/km.

fiber optic – Pertaining to optical fiber systems, such as sensors and communication systems.

fiber optic cable – Optical fibers incorporated into a cable. See cable.

fiber optic data link – A data link consisting of a modulated light source, a fiber optic cable, and a photo-detector.

fiber optics (FO) – The theory and practices of using the technologies for control and guidance of optical power.

fiber optic sensor – A sensor in which light is modulated by a specified environmental variable.

fiber optic sheath – An outer protective covering over an optical fiber, or cable.

fiber optic splice – A non-separable junction, usually formed by fusing the end of one optical conductor to another.

frequency-division multiplexing (FDM) – Multiplexing in which the transmission frequency range is divided into narrow bands, each used as a separate channel.

G

graded-index fiber – An optical fiber with a refractive index that gets progressively lower as the distance increases along the normal to the fiber axis.

H

heterodyne detection – Signal detection based on the mixing of two frequencies.

heterodyning – The mixing of an electromagnetic wave of one frequency with a wave of another frequency to produce a beat, usually for demodulation.

homodyne detection – Signal detection based on the use of only one frequency.

I

incident ray – A ray of light that strikes, the surface of any object.

index-matching material – A light-conducting material used to reduce optical power losses, usually in connectors.

intensity sensor – In fiber optics, a fiber optic sensor in which the optical intensity of a light beam varies with an environmental signal. A micro-bend sensor.

interferometer – An instrument in which the interference effects of light waves are used for purposes of measurement.

interferometric sensor – A sensor that employs the principles of interferometry to perform a sensing function.

interferometry – The study of electromagnetic wave interference for precise measurements of things such as wavelength determination and index of refraction.

internal reflection – A reflection at an outside surface from the inside such that an incident wave is reflected wholly or in part back into the element itself.

intrinsic fiber loss – Optical power loss in an optical fiber or coupling.

isotropic material – A substance that exhibits the same property when tested along an axis in all directions.

K

Kerr cell – A substance, usually a liquid, with a refractive index change proportional to the square of an applied electric field. The cell can provide a means of modulating the light in the optical path.

L

LED – See light emitting diode.

laser – A coherent-light source used to generate an intense, highly directional, narrow beam of electromagnetic energy.

light-emitting diode (LED) – A diode without lasing action. The output is about 10 times the spectral width of a laser.

light ray – A line perpendicular to the wave front of a light wave indicating direction of propagation.

light source – Any device that produces light.

loss – Optical power loss in a fiber system.

M

Mach-Zehnder interferometer – An interferometer in which the light wave is split, and then recombined at a photo-detector.

magneto-optic – Pertaining to the action of a magnetic field on light waves.

magneto-optic modulator – A modulator that uses a magnetic field to modulate a light wave.

Michelson interferometer – An interferometer in which an electromagnetic wave is split and recombined so that displacement measurements can be made by fringe counting. (Very cheap method if graduate students are used)

microbend – A bend in the optical fiber with a radius equal to or smaller than the critical radius causing light waves in the core to penetrate into the cladding and leak from the fiber.

microbend loss – The signal attenuation caused by microbending.

microbend sensor – A sensor that converts mechanical movement to fiber bending so that the output light wave intensity is proportional to the mechanical movement.

micron – 10^{-6} meter. Synonymous with micrometer.

mode – The characteristic state of a specific light beam traveling in a fiber. The mode is a function of the core diameter, the index of refraction of the core and cladding, and the wavelength of the light.

modulation – The impressed variations of a carrier wave that correspond to an input signal.

modulator – A device that modulates a carrier.

moving grating sensor – A sensor consisting of both a fixed and moveable grating so that the intensity of light passing through the gratings is modulated according to the motion of the movable grating.

multimode fiber – An optical fiber waveguide that will support more than one mode.

multiplexing – A method of transmitting several signals on the same channel.

N

nanometer – 10^{-9} meter.

noise – Unwanted energy that degrades or masks the desired signals.

numerical aperture (N.A.) – A measure of the light-accepting ability of an optical fiber.

O

optical fiber – An optical waveguide usually consisting of a glass core and glass cladding.

optical fiber coating – A protective material this is put over the cladding to help protect the glass fiber from mechanical damage.

optical fiber jacket – A material used to cover an optical fiber, whether or not it is cladded or coated.

optical fiber loss – The optical power loss in an optical fiber, usually expressed in dB/km.

optical power budget – In a fiber optic system, the power for each element of the system that is required to keep the signals above specified distortion limits or error rates.

optical repeater – A signal amplification, processing, and re-transmitting device.

optical sensor – See fiber optic sensor.

P

phase modulation (PM) – Modulation of the carrier wave phase angle to follow an environmental signal.

photo-detector (PD) – A device that outputs an electrical signal proportional to the amplitude of the incoming light.

polarimetric sensor – A sensor in which the environmental signal alters the polarization of a light wave in an optical fiber.

polarization – The property of a radiated electromagnetic wave that describes the time-varying direction and amplitude of the electric field vector.

polarization modulation – The modulation of a carrier wave by changing the direction, amplitude, and/or phase of the electric field vector of an information-bearing input signal.

polarization multiplexing – Multiplexing by using two or more polarization modes in the same transmission medium at the same time with the same frequency. Each mode is a separate channel.

power budget – The allocation of available power in a system to the various functions that need to be performed.

R

Rayleigh scattering – The scattering of light waves due to small particles in the medium.

reflected ray – A ray representing the light wave leaving a reflective surface and indicating the path at reflection.

reflection – The return of a light wave from a surface.

refractive index – The ratio of the velocity of light in a vacuum to the velocity of the same light in a new medium is the refractive index of the new medium.

S

Sagnac interferometer – An interferometer in which a light wave is split and passed in opposite directions through a coil to measure angular acceleration.

scattering – The deflection of electromagnetic waves caused by all the influences within the medium.

sensor – Any device that responds to an environmental signal and outputs a signal that can be used as a measure of the environmental signal.

sensor array – A spatial distribution of sensors.

single-mode fiber – An optical fiber that supports the propagation of one mode, usually a low-loss optical waveguide with a very small core.

source – The part of a system from which signals or messages originate.

space-division multiplexing – The use of spatial separation to obtain channel isolation.

splitter – See beam splitter.

step-index fiber – A fiber manufactured with a fixed index of refraction for the core and cladding, with the cladding index being less than that of the core.

T

time-division multiplexing (TDM) – Multiplexing in which separate channels are established by connecting one circuit to many signal sources sequentially in time.

total internal reflection – Reflection that occurs in a medium when the incidence angle of a light ray striking a boundary of the medium is greater than the critical angle and the entire energy of the ray is reflected back into the medium.

transducer – See sensor.

W

waveguide – Any structure capable of confining and supporting the energy of an electromagnetic wave.

waveguide delay distortion – The distortion of the signal that is caused by the different velocities for each wavelength.

waveguide dispersion – The part of the total dispersion attributable to the dimensions of the waveguide.

wavelength – The length of a wave measured from any point on a wave to the corresponding point on the next cycle of the wave.

wavelength-division multiplexing (WDM) – The multiplexing of light waves in a single transmission medium, such that different wavelengths are responsible for the channel separation.

1.0 OVERVIEW

1.1 FOREWORD

What follows is an overview of how fiber optic sensors may be used to analyze infrastructure systems by sensing strain; temperature, pressure and other key parameters. An introduction to the basics of optical fibers will be presented, followed by an overview of fiber optic sensor technology. Then more detailed discussions on several fiber optic sensor types of particular importance to infrastructure applications will be given, along with examples of actual applications from the literature.

This overview is intended to offer a summary of the possibilities for fiber optic technology, as well as indicate where to find relevant information quickly and easily.

1.2 FIBER OPTIC SENSOR TECHNOLOGY FOR INFRASTRUCTURE SYSTEMS

Fiber optic sensors are based on literally hair thin optical fiber, typically ranging from 75 microns (3 mils) to 125 microns (5 mils) in diameter. They can be configured to measure a wide range of effects via changes in light beams that are propagating through the optical fibers. Important parameters for infrastructure applications that may be measured include longitudinal and transverse strain, pressure, temperature, and corrosion.

1.2.1 Key Features

Key features of fiber optic sensor technology that makes its use compelling for infrastructure applications are:

1.2.1.1 Immunity to Electromagnetic Interference

Shielding requirements and problems associated with ground loops, lightning strikes and electrical hazards are eliminated.

1.2.1.2 Very Small Size

These sensors can be placed in structural materials without degrading structural integrity, which also makes the fiber sensors a much less obvious target for vandals and thieves.

1.2.1.3 Environmental Ruggedness

Fiber sensors can operate at high and low temperatures and can be embedded in composite materials.

1.2.1.4 The Ability to Multiplex Many Fiber Optic Sensors

These sensors with large dynamic ranges and high frequency responses are located along a single fiber line, since the bandwidth of the connecting optical fiber is extremely large.

1.2.1.5 Possible Low Cost, High Performance Devices in Future

A high degree of synergy with the telecommunication and optoelectronic markets make the prospect of low cost, high performance devices very likely in the future.

1.2.1.6 Multifunctional Capabilities

A series of parameters can be sensed along the same fiber line simultaneously, such as multi-axis strain, pressure, corrosion, temperature, and, the location and measurement of an acoustic signal.

1.2.1.7 A Wide Range of Sensor Gauge Lengths

Even though fiber optic sensors possess a wide range of gauge lengths, ranging from less than one mm to many kilometers, and have the ability to use fiber optic demodulators many kilometers from the sensors themselves, this does not significantly affect the signal to noise ratio.

These features allow the designer of fiber optic sensor systems for infrastructure to have a range of options that are unavailable using conventional sensor based technology.

1.2.2 Categories

There are four categories for fiber optic sensors in infrastructure applications:

1.2.2.1 Attached or Embedded Sensors

Fiber optic sensors may be embedded or attached to a structure to monitor the manufacturing processes for large sections. An example of this type of application is the monitoring of the temperature distribution in large concrete pads as they are being cured.

1.2.2.2 Nondestructive Testing of Parts Prior to Installation

In this case the fiber sensors, which could also have been used to augment the manufacturing process, can be used to evaluate the properties of a part before it is installed. This process could involve using embedded fiber optic sensors or fiber optic acoustic detectors in combination with ultrasonic transducers, to measure changes in strain fields.

1.2.2.3 Health Monitoring Systems

Arrays of fiber optic sensors are deployed to assess the condition of a structure. An example of this type of application would involve strain sensors deployed at important locations on a bridge.

1.2.2.4 Control Systems

The fiber sensor system is used to not only collect environmental data, but to react to the data. An example might be a highway that senses an accident and activates warning signs as a result.

1.3 SELECTED APPLICATION EXAMPLES

One way to look at fiber sensor systems as they apply to future infrastructure applications is to consider the optical fibers with fiber optic sensors to be a nerve system. The optical fibers are the information carrier and along their length are the fiber sensors, or nerve endings, which are used to sense the environment. Because of their very small size and light weight, and perhaps most importantly, high immunity to electromagnetic interference, they can be incorporated, virtually without effect, in the infrastructure, much like nerves in a body.

The information from these optical fibers, or nerves, and fiber optic sensors, or nerve endings, is carried to optical/electronic demodulators that do a rudimentary sort of the information similar to the lower part of the brain. This first level processing is similar to an overall awareness level of nerves in a human body. For some fiber optic sensor systems this is all the sophistication required. Environmental effects are simply recorded when they happen. In the future, however, large systems integrated into bridges, tunnels, large sections of highways or retaining walls may require very large numbers of sensors, perhaps numbering in the thousands. When something happens to an area of such a large structure that requires additional processing, the demodulated signals may be subject to considerable post processing, an action similar to higher order brain functioning.

The basic idea behind systems involving very large numbers of sensors deployed in a sophisticated system, again, has analogies to the human body and its nervous system. Consider the case of a little league baseball player who is batting. The pitcher throws a ball and he is hit on the arm. His first level of awareness is that he has been hit on the arm. His nerves identify the location of the damage and he then looks it over carefully to assess the area condition: swelling, redness, bleeding and so forth. When this batter is batting, not all of his nerves are firing and demanding attention all at once. If this happened the batter could not function, as his brain processor would be overwhelmed. Instead, his brain is provided with a low-level situational awareness. When he is hit, his low level brain functions indicate an area of pain, and the higher order brain functions take over to do a detailed assessment.

Consider a bridge with thousands of fiber optic sensors deployed to perform detailed health and damage assessment. The sensor system would also execute high performance functions that would include calling for help to repair damaged areas when required, and in extreme cases, closing itself. The signals from these many sensors would be used to provide the sensor data processor with an overall status of the health of the bridge at a low level. When damage occurs, such as a barge slamming into a piling, the low-level signals from the fiber sensor system would indicate the location of the damage. Then the level of interrogation of the sensors would be reconfigured so that a detailed assessment of the damage could be made and appropriate action taken.

In the following paragraphs a series of application examples are given.

1.3.1 Concrete Cure Monitoring

Some fiber optic sensors are capable of measuring a parameter over long distances. The example shown in Figure 1.1 is a commercial fiber optic temperature sensor that consists of a hair thin fiber that can be placed into a concrete structure and used to measure temperature. It can measure to within a couple of degrees C with approximately 1 to 2 m resolution over distances that may be approximately 3 to 5 kilometers. This system has been used to monitor the temperature distribution over large, thick concrete pads as they are setting and curing.

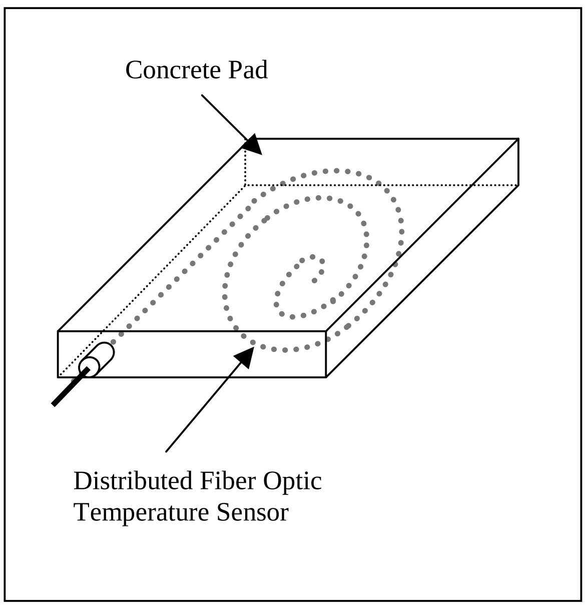


Figure 1.1: Embedded temperature sensor to measure curing of thick concrete pad

1.3.2 Retaining Wall Anchor

One essential infrastructure application that is of particular interest to Oregon is to measure the forces on retaining walls that are used to prevent slides. Examples of how fiber optic sensors could be used in this case would include fiber optic strain sensors placed along the length of retaining wall anchors to measure strain gradients, as shown in Figure 1.2. Another example would be to place the fiber strain sensors into the wall face to measure strain field distributions and changes in loading to predict the likelihood of wall distress.

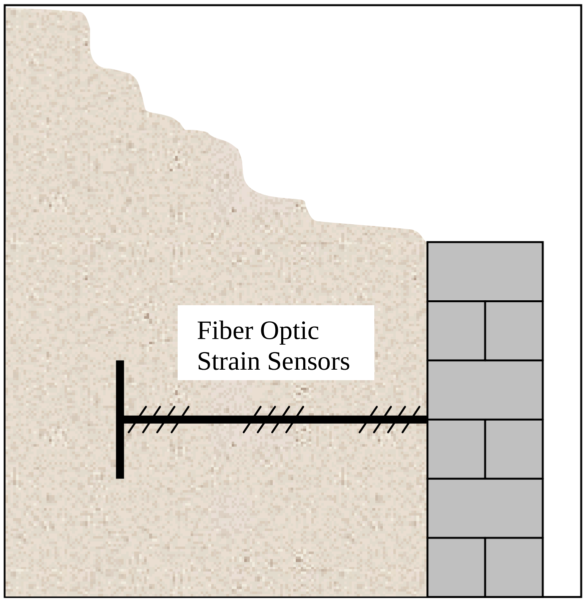


Figure 1.2: Strain sensors on retaining wall anchor

1.3.3 Tunnels

Transverse and longitudinal strain may be measured using a fiber optic sensor network. This can be done at many point locations on the ceiling of the tunnel, as well as, on sidewalls. Because fiber sensors can have both very long or very short gauge lengths ranging from millimeters to kilometers, the designer has a wide choice of strain sensing options to deploy for an appropriate health monitoring system. Figure 1.3 shows a fiber optic sensor system deployed to measure strain distribution in a tunnel. Other possible uses for fiber optic sensors in tunnels would be to measure critical points of corrosion on rebar and other reinforcing structures.

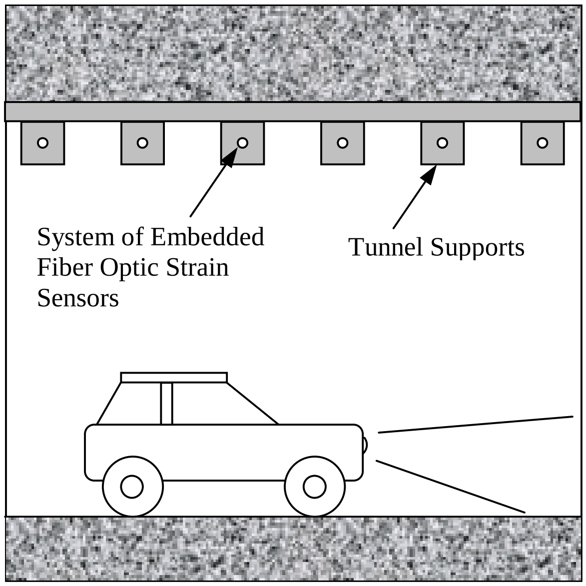


Figure 1.3: System of strain sensors to monitor condition of tunnels

1.3.4 Torque Measurements

A fiber strain sensor could be embedded into composite washers and used to measure the amount of loading, ensuring that the correct amount of torque was applied during installation. Subsequently, the loading could be measured periodically, either automatically or by an inspector, to ensure that the proper loading is maintained.

1.3.5 Corrosion Sensors

One of the essential issues for many infrastructure systems is corrosion. Because of their very small size, fiber sensors could be placed at important points in the structure and be used to measure corrosion on rebar. Fiber sensors offer the prospect of measuring corrosion at many points over a widely distributed area with high performance and cost effectiveness.

1.3.6 Suspension Bridges

An array of axial fiber optic strain sensors could be used to monitor strain on cables as shown in Figure 1.4. Other fiber sensors could be used to measure corrosion at important locations, scour and bolt torque.

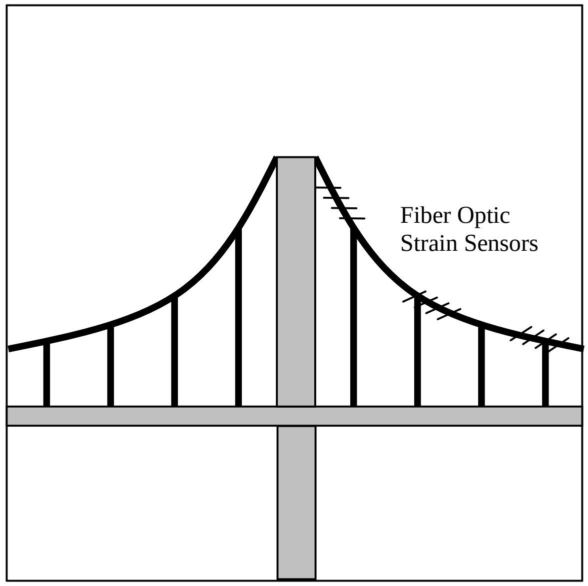


Figure 1.4: Strain sensors on suspension bridge

1.3.7 Drawbridges

Transverse fiber optic strain sensors could be embedded into composite panels that are used to measure loading of counterweights on drawbridges, ensuring that the roadbed remains properly seated, as in Figure 1.5.

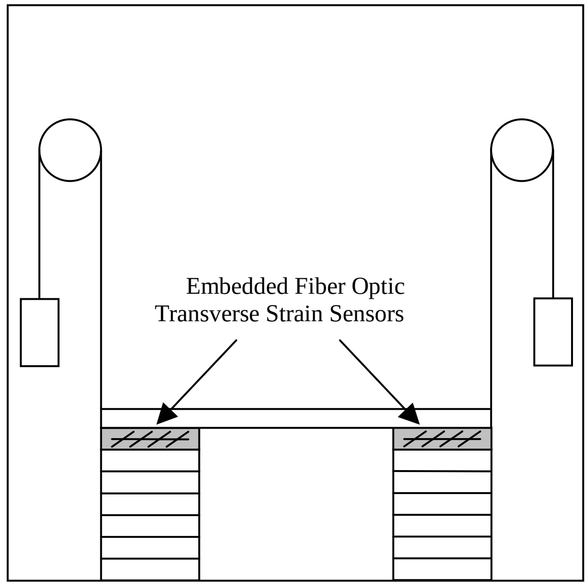


Figure 1.5: Strain sensors embedded in supports to measure the balance of a drawbridge

1.3.8 Truss Monitoring

Fiber optic strain sensors can be embedded into composite reinforcing trusses, which could be used to enhance the strength of existing bridges, as in Figure 1.6. Fiber sensors could also be applied to the surface of steel structures and used to compare strain values for both the steel and the reinforcing composite structures.

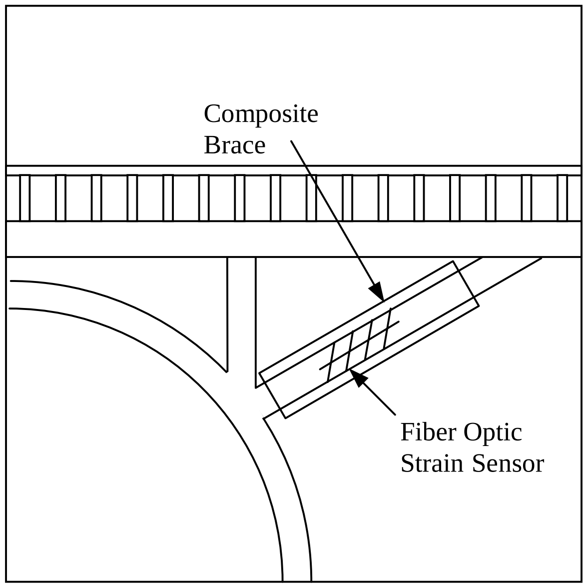


Figure 1.6: Strain sensor monitoring truss reinforced with composite brace

1.3.9 Acoustic Sensors

Fiber optic sensors can be used to measure the amplitude and location of an acoustic disturbance over distances that may be tens of kilometers long. Systems of this type could be used to measure the location of potholes and the extent of damage to bridges and roads. It is also possible that these systems could be used to indicate the occurrence of an accident and its location, although this system might require more sophisticated data processing than road or bridge deck damage assessment. (Figure 1.7)

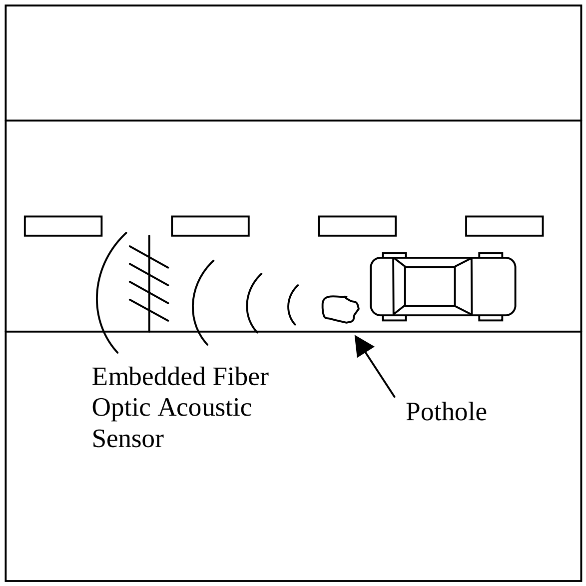


Figure 1.7: Acoustic sensor to detect anomalies in roads, bridges, railway tracks, etc.

1.3.10 Soil Measurement

Arrays of fiber optic pressure sensors could be used to perform such critical geotechnical measurements as water content and compaction of the soil before, during and after infrastructure construction operations.

1.3.11 Traffic Control

Transverse strain sensors embedded in roads can control automatic turn lanes, etc. (Figure 1.8)

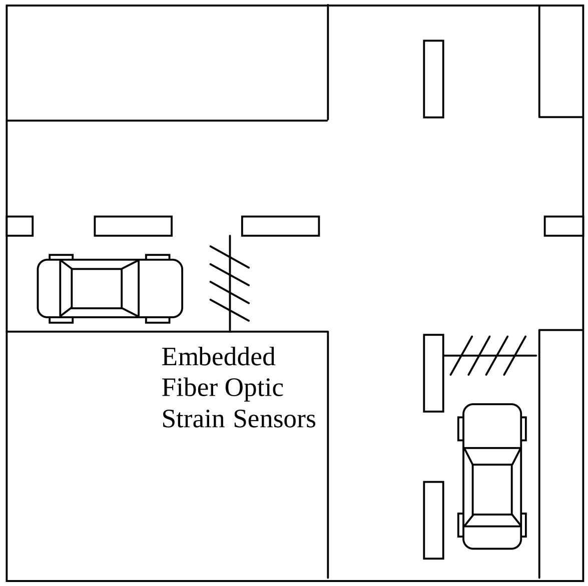


Figure 1.8: Strain sensors for traffic control

1.3.12 Traffic Monitoring

An array of strain sensors embedded in roads can monitor the speed and weight of cars and trucks. (Figure 1.9)

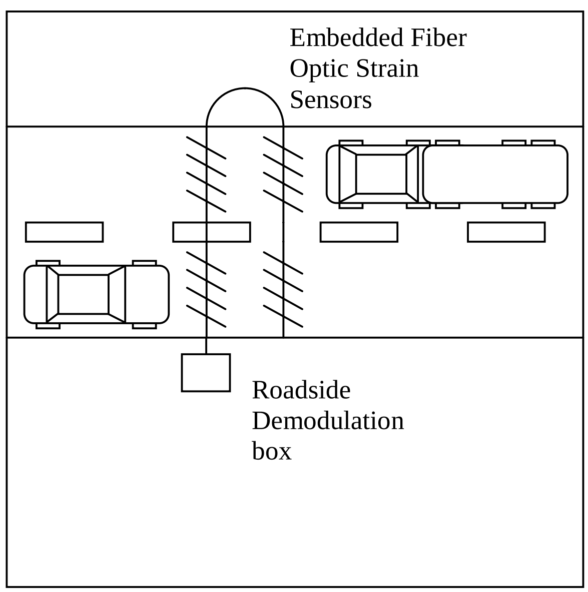


Figure 1.9: Strain sensors for speed and weight measurements

1.3.13 Road Conditions

An example of a road-weather condition monitor is a Fiber Bragg Grating ice sensor. This sensor can detect ice on the road and trigger an action, such as posting warning on electronic signing in the area.

1.4 WHERE TO FIND ADDITIONAL INFORMATION IN THIS REPORT

Table 1.1: Report Contents

CHAPTER	**BRIEF DESCRIPTION**
CHAPTER 1 Overview	The report begins with this brief summary of Fiber Optic Sensor Technology Possibilities
CHAPTER 2 Introduction to Fiber Optic Basics	The basic theory and operation of optical fibers are reviewed. Read this first if an understanding of basic fiber optics is desired. If not, proceed to Chapter 3.
CHAPTER 3 Introduction to Fiber Optic Sensors	An overview of the technology and applications is covered. Start here to get right into fiber sensor basics. Refer back to Chapter 2 if fiber optic basics are desired.
CHAPTER 4 General Introduction to Fiber Optic Sensors for Transportation Infrastructure Applications	A further description is offered of fiber optic sensors that are useful for infrastructure applications: microbend, grating, etalon, and interferometric fiber sensors.
CHAPTER 5 Synthesis of Sensor Applications	Some fiber optic sensor infrastructure uses from the literature are summarized. For more detail, refer back to descriptions of sensor types in Chapter 4.
APPENDIX A AND B A. Installation Techniques for Fiber Optic Sensors B. Procedure for Cleaning Connectors	Practical advice associated with handling fiber optics is discussed.

This report may be used in several different ways as seen in Table 1.1. For an overview of fiber optic sensor technology with a basic discussion of the underlying physics, Chapter 2 may be an appropriate place to start. For applications, proceed to Chapter 5, referring back to earlier chapters only as necessary. While an attempt has been made to make the chapters as independent and readable as possible, a complete understanding of some of the sensing techniques may require careful study of all of the chapters and many of the references. A large number of drawings have been included in the report to help in understanding the implications of fiber optic sensor technology. The appendices include some of the techniques involved in handling and installing fiber optic sensor technology. While the skills are somewhat different from those associated with electrical sensors they are readily learned and are simpler than their electrical equivalents. For a summary of the different types of fiber optic sensors available for infrastructure applications, see Table 1.2.

1.5 SUMMARY

Fiber optic sensor technology offers the possibility of implementing "nervous systems" for infrastructure elements that allow high performance, cost effective health and damage assessment systems to be achieved. This is possible, largely due to synergistic developments in the fiber optic telecommunication and optoelectronics fields, where industries with multi-billion dollar research and development budgets exist. Now, essential components are becoming available with prices and performance that are improving dramatically on an annual basis. This report is an introduction to fiber optics, fiber optic sensor technology and some of the applications that make this field, which is still in its early infancy, one of the most promising new developments in infrastructure systems.

Table 1.2: Summary of Fiber Optic Sensors

TYPE OF SENSOR	APPLICATION	ADVANTAGES	DISADVANTAGES
Microbend Sensors	Measure qualitative information through the loss of light: safety mats in front of rotating machinery that disable machines when operator is at unsafe location, fire detection in large buildings, excess stress locations for pipelines	Low cost; possible coverage of wide area	Low accuracy
Extrinsic Fabry-Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: single point static strain measurements in experiments and manufacturing processes for structures and bridges, pressure measurements	Gauge lengths similar to conventional strain gauges; immunity to electromagnetic interference; high temperature, shock & vibration resistant	Difficulties associated with measuring temperature and strain simultaneously, which may be important for internal measurements in inaccessible areas
Intrinsic Fabry-Perot Fiber Etalon Sensors	Measure longitudinal component of strain, pressure or temperature through two mirrored surfaces: time varying strain measurement applications, including strain on cylinder heads operating at elevated temperatures, vibrating machinery and dynamic loads on railway bridges	Gauge lengths similar to conventional strain gauges; immunity to electromagnetic interference; high temperature, shock & vibration resistant	Difficulties associated with measuring temperature and strain simultaneously, which may be important for internal measurements in inaccessible areas
Fiber Grating Sensors	Measure an index of refraction modulation of the fiber core produced by an interference pattern formed through the fiber: strain on bridges, aircraft parts , naval vessel parts and utility poles, compared to the same measurements from conventional electric strain gauges	Possible future low cost; multiparameter sensing of transverse & longitudinal strain, strain gradients, temperature, pressure and corrosion	Expensive, due to limited production and use
Mach Zehnder and Michelson Interferometric Sensors	Measure acoustic waves and vibration, both the time varying and static quantities, since strain, temperature and pressure all affect their response: Undersea surveillance and geophysical seismic exploration.	Extremely flexible geometry and high sensitivity, wide area distribution	High cost; the long coherence length lasing light sources required are not as reliable and cannot handle as high of temperatures as the light source for the Sagnac sensor.
Sagnac Interferometric Sensors	Filters lower frequency noise components, optimum performance with low coherence light source that has higher reliability & ability to withstand higher temperatures than other interferometers, and distributed sensing capabilities	Rapidly emerging industrial base for this type of interferometer only; environmental ruggedness	Response at low frequencies is linearly proportional to frequency; does not have high sensitivity for detection of low frequency signals

2.0 INTRODUCTION TO FIBER OPTIC BASICS

2.1 BASIC PHYSICS OF LIGHT

Electromagnetic radiation visible to the human eye is generally referred to as light, however, electromagnetic radiation not visible to the human eye is continuously being emitted and absorbed all around us at all times. The vast majority of the electromagnetic energy emitted by the sun is in the infrared region and is not visible. Our eyes are detectors that only respond to electromagnetic radiation within certain energy levels. The carriers of electromagnetic radiation are often referred to as “photons”; however, dealing with individual photons is very complex and thus is limited in scope in this discussion. The study of light as “groups of photons” or “waves” has been underway for hundreds of years. Many excellent books have been written that discuss the history and nature of light (*Born; Heavens; Hecht; Jenkins; Klein; Meyer-Arendt; Young, H.; Young, M.*). In this section, the basic fundamental principles of light, useful for understanding optical fiber technology, are presented.

2.1.1 Photons

Except in the limit of extremely low light levels, a study of individual photons is not needed to understand most of optical fiber technology. Certain facts regarding photons are important, as they often are compared to electrons and electrical current, and are important for understanding how light interacts with matter such as glass or liquids. Further, large quantities of photons must be detected (and possibly measured) to determine their approximate number, and perhaps their distribution of wavelengths, or even their polarization properties. To that end, basic relationships between energy, velocity, wavelength, and frequency of light are introduced. In the following, SI (MKS) units are used.

2.1.1.1 Energy, Velocity, Wavelength, and Frequency

Photons may be characterized by their energy-wavelength-frequency-velocity relationship. In it’s simplest form, the energy of a photon E (Joules), is equal to Planck’s constant h (6.63 x 10-34 Joules · second) times the frequency f (cycles/second or “Hz”) of the light:

$$E = hf \tag{2-1}$$

Frequency is related to velocity v (meters/sec) and wavelength λ (meters) [pronounced ‘lambda’], as follows:

$$f = \frac{v}{\lambda} \tag{2-2}$$

Therefore, energy can be related to velocity, and wavelength or frequency:

$$E = \frac{hv}{\lambda} \tag{2-3}$$

Wavelength is usually measured in microns (10^{-6} meters). With these simple relationships, it is easy to determine the energy of a photon, once the wavelength is known, or vice versa. Such determinations are common when analyzing the interaction of photons with various types of detectors, chemicals, or materials that may be utilized in fiber optic sensors. It is the energy of a photon that determines how a detector will respond to it. While optical fiber technologies utilize light throughout the electromagnetic spectrum, many applications do not use visible light. Figure 2.1 depicts the electromagnetic spectrum, the portion within which fiber technologies may operate, and the visible spectrum.

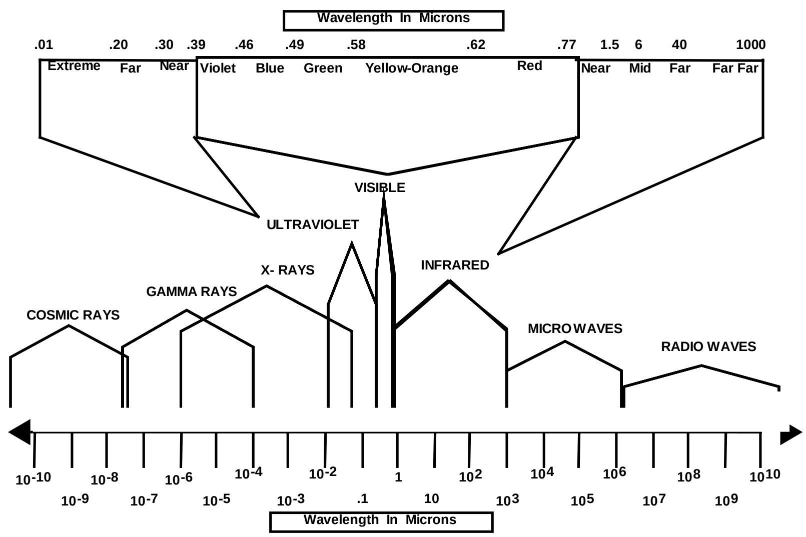


Figure 2.1: Electromagnetic spectrum

2.1.1.2 Polarization

Another characteristic of light finding increasing application in both telecommunications and sensors, is polarization. Again, large numbers of photons, not individual photons, are assumed and electromagnetic waves are considered. (A good treatment of polarization is provided in: (*Collett*))

Polarization refers to the orientation of the electric field of the electromagnetic wave. While this may sound complicated, it actually is very simple if an ordinary "linear" polarizer such as is common in sunglasses and certain camera filters is considered. (This discussion is restricted to "linear" polarization.) Figure 2.2 depicts unpolarized light incident on an ideal linear polarizer. Only the light whose electric field component aligns with the transmission axis of the polarizer will pass through the polarizer. It is easy to see that another polarizer whose transmission axis is perpendicular to the first polarizer, (ideally) will not allow light to pass through the second polarizer. (Figure 2.3)**.** A basic concept here is that electromagnetic waves can be represented as "transverse" vibrations, where the vibration is perpendicular to the direction of travel. (Figure 2.4)**.**

This characteristic of light is immensely important in certain singlemode “coherent” sensors, such as Sagnac-based interferometric sensors (*Udd, 1991a*) and in some multimode fiber optic sensors.

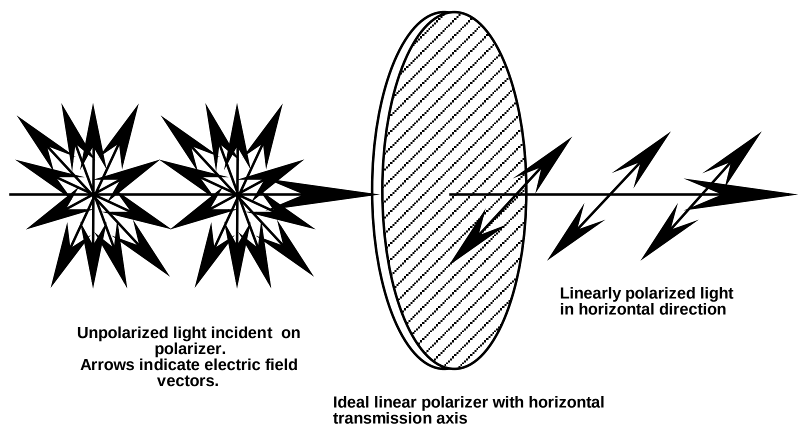


Figure 2.2: Unpolarized light incident on ideal linear polarizer

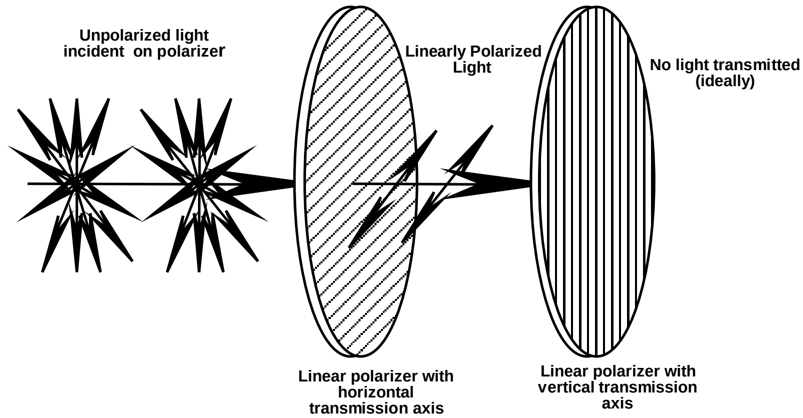


Figure 2.3: Unpolarized light incident on two crossed polarizers

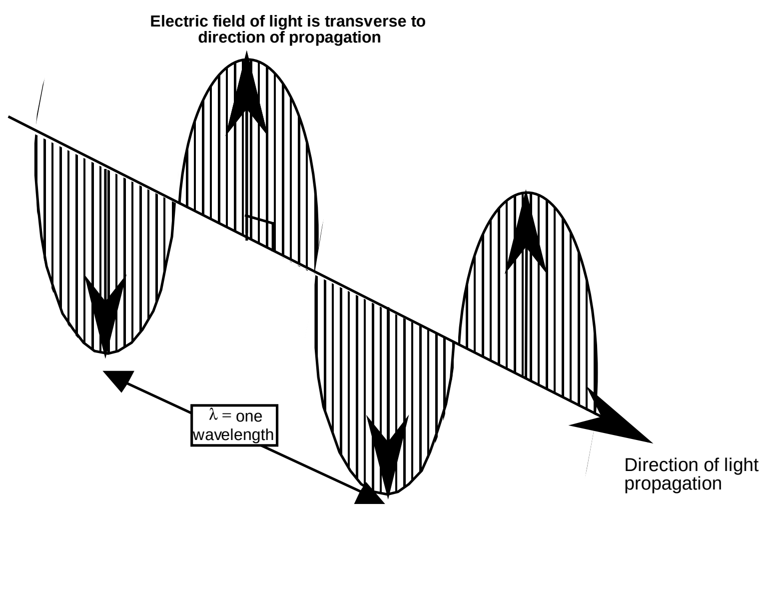


Figure 2.4: Electric field of light as transverse wave (shown vertically polarized)

2.1.2 Light models

In section 2.1.1, the distinction between considering individual photons and large numbers of photons was mentioned. To treat individual photons requires considerable mathematics, advanced electromagnetic theory, and quantum mechanics. Luckily, most fiber optics applications require large numbers of photons; therefore, in depth study of individual photons is not necessary. All further discussions will assume large numbers of photons unless specifically noted otherwise.

Next follows some useful models for understanding how light behaves in fibers. The "ray" model provides a handy, geometric perspective on light within fibers. The wave model is necessary for understanding phenomena such as interference, important in certain fiber sensors, as discussed in (*Udd, 1991a*).

2.1.2.1 Light as 'Rays'

When a large number of photons are propagating together in a particular direction, a "ray" is conveniently overlaid indicating the direction of light-propagation. The photons do not necessarily have to have the same wavelength, a good example being light from the sun. The sun emits photons with a wide range of wavelengths but only those within the visible spectrum are seen; however, radiation outside of the visible spectrum also is present, and visible light is a very small portion of the total emitted radiation. Figure 2.5 represents light being emitted from different types of sources and the rays are used to indicate that light is being emitted in certain directions.

2.1.2.2 Light as 'Waves'

Since light moves from one place to another, it should not be too surprising that it is considered a "wave" of electromagnetic energy. Light is not considered to be the same kind of wave as sound waves, which require some kind of material to move through. Light will move, "on its own" through a vacuum. (This phenomenon, while known, is not totally understood. Electromagnetic equations exist that describe this, but *why* light does this still is not clear.)

Often, light from a source will be depicted with planes (typically called "wavefronts",) drawn perpendicular to the rays described in the last section, Figure 2.6. This is useful for understanding that photons of light from a source all have a different trajectory as they leave the source, and eventually diverge from each other, unless optical elements or systems are used to control and direct the light (e.g., mirrors, lenses, gratings, prisms, interferometers, and so on). When close to the source, the difference in trajectory may be small, however when far away from the source, the difference in trajectory may be very important, and have important consequences on system performance. This property is referred to as spatial coherence, and is very important in a number of applications. In Figure 2.5, it is seen that the spatial coherence of a laser is much greater than light from any other source.

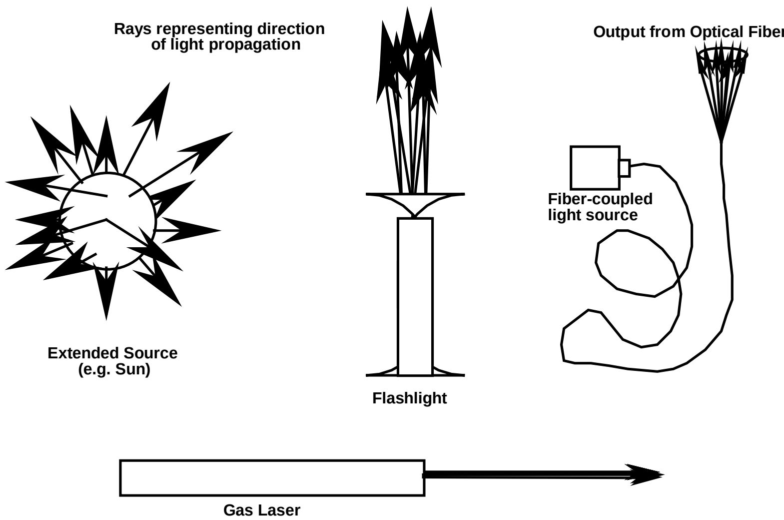


Figure 2.5: Rays of light from various sources

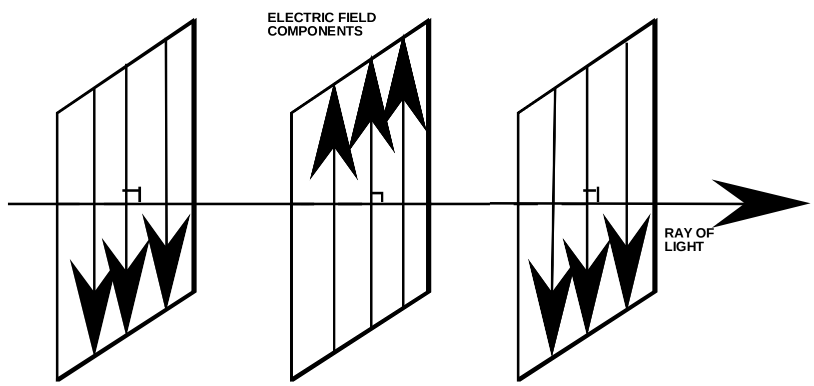


Figure 2.6: Plane-wavefronts

In some sources, like thermal objects that radiate in many directions, the difference in trajectory may be very large at the emitting surface thus the spatial coherence is very low. Thermal sources are uncommon in fiber technology applications.

An important sensor technology that is known as interferometry relies on the wave properties of light. Optical interferometry has been extensively developed since the laser was created, and now is finding increasing application utilizing fiber technology.

2.2 OPTICAL FIBERS

A first step to understanding optical fibers is to think of them as light "pipes", in which light actually reflects from the inside surface, which could be thought of as a mirror. In fact, this surprisingly useful model leads to the understanding of the physics that enables optical fibers to transmit light. The principle of total internal reflection, which is the basis for this model of "guiding light", relies on understanding the index of refraction.

2.2.1 Index of Refraction

As previously discussed, light propagates through a vacuum, needing no material such as air or water, as do sound waves. In a vacuum, the velocity of light is $2.997 \cdot 10^8$ meters / sec. However, when light encounters a material such as air, water, glass, or any type of gas, liquid, or solid, the light's velocity (v) changes. When the light's velocity changes, the ratio of the speed of light in a vacuum to the speed of light in the material is known as the index of refraction ("n", which is unitless, since it is a ratio). In most materials, the index of refraction varies as a function of the direction of propagation of the light, as well as the frequency of the light. For this discussion however, the index of refraction is considered to be independent of direction and frequency:

$$n = \frac{c}{v}. \tag{2-4}$$

Table 1 provides a listing of indices of refraction for a variety of different materials (*Halliday*). The index of refraction always will be greater than 1.0

2.2.1.1 Snell's Law

Using the ray model and Snell's law, which is a simple geometric relationship that describes what happens to light at a smooth interface between two materials with different indices of refraction, the basic foundation for optical fiber technology can be understood. (Smooth, "polished-like" surfaces, as opposed to rough, "diffuse" surfaces, are assumed.) For example, when light from the sun hits water, some of the light is reflected, and some is transmitted into the water. The light transmitted into the water is referred to as "refracted" light, because the direction of propagation is changed at the interface between the air and the water. This is depicted in Figure 2.7. If n_i is the index of refraction for the medium where the incident light is and n_t for the transmitted light medium, then, Snell's law is as follows:

$$n_i(\sin\theta_i) = n_t(\sin\theta_t) \tag{2-5}$$

Where θ_i, θ_t are the incident and transmitted angles as shown. (Note that these angles are determined from the normal to the surface.)

Table 2.1: Indices of Refraction of Various Materials at .589 Microns (*Halliday*)

MATERIAL	INDEX OF REFRACTION
Air (1 atm and 20°C)	1.0003
Water	1.33
Ethyl Alcohol	1.36
Carbon Bisulfide	1.63
Methylene iodide	1.74
Fused quartz	1.46
Glass, crown	1.52
Glass, dense flint	1.66
Sodium chloride	1.53

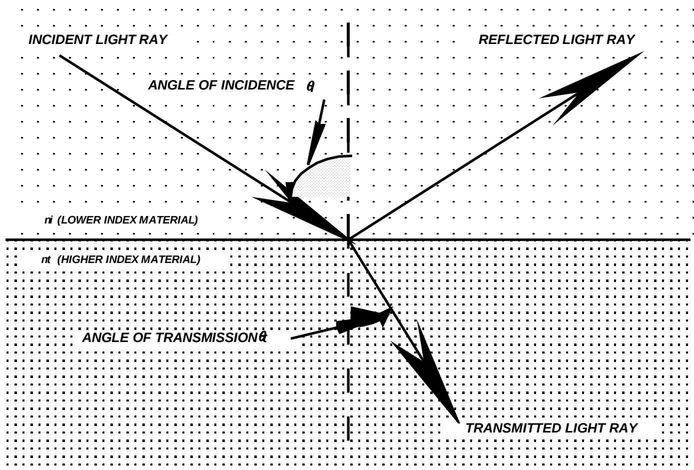


Figure 2.7: Snell's law for lower index to higher index

With this relationship, it then can be determined what the refraction angle is, assuming the index of refraction for the air is approximately 1.0 and water is 1.3, the refraction angle can be computed from rearranging Snell's law to obtain:

$$\theta_t = \sin^{-1}\left(\frac{n_i}{n_t}\sin\theta_i\right) = \sin^{-1}\left(\frac{1.0}{1.3}\sin\theta_i\right) = \sin^{-1}\left(0.77\sin\theta_i\right) \qquad \textbf{(2-6)}$$

For example, if the incident sun angle was 45°, then:

$$\theta_t = \sin^{-1}\left[\{0.77\}\{0.71\}\right] = \sin^{-1}(0.55) = 33$$

Since sin(45°) = 0.707 and sin(33°) = 0.55, Figure 2.8.

The angle of the reflected light (θ_r) also obeys Snell's law, however, the index of refraction of the medium for both the incident and reflected light (n_r) is the same. Then: from Equation 2-5:

$$\sin\theta_i = \sin\theta_r \;\; or \;\; \theta_i = \theta_r \tag{2-7}$$

, since $n_i = n_r$, Figure 2.9.

Now, from basic physics, apply the law of conservation of energy to the incident light. All light that is incident on the material must be transmitted, reflected, or absorbed. For this assessment a negligible amount of the light is assumed to be absorbed. Consequently, all light not transmitted will be reflected. Assume the integer value 1 represents the light incident energy, and let R and T represent the reflected and transmitted light energy, then:

$$R + T = 1 \text{ or } R = T - 1 \tag{2-8}$$

As a result, all light not transmitted is reflected.

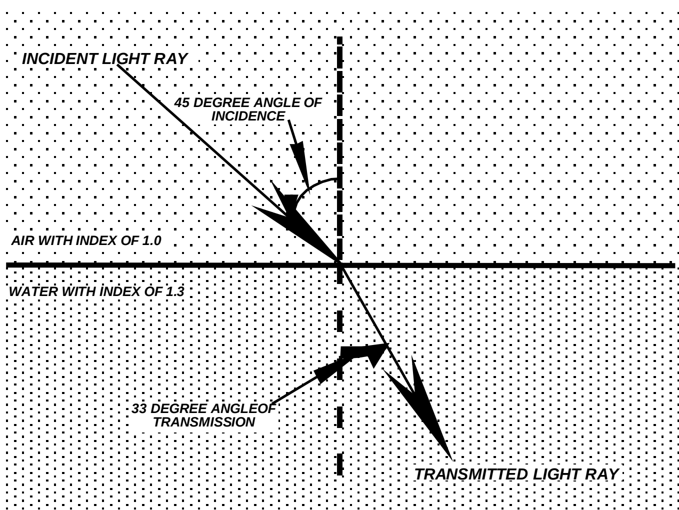


Figure 2.8: Air to water interface

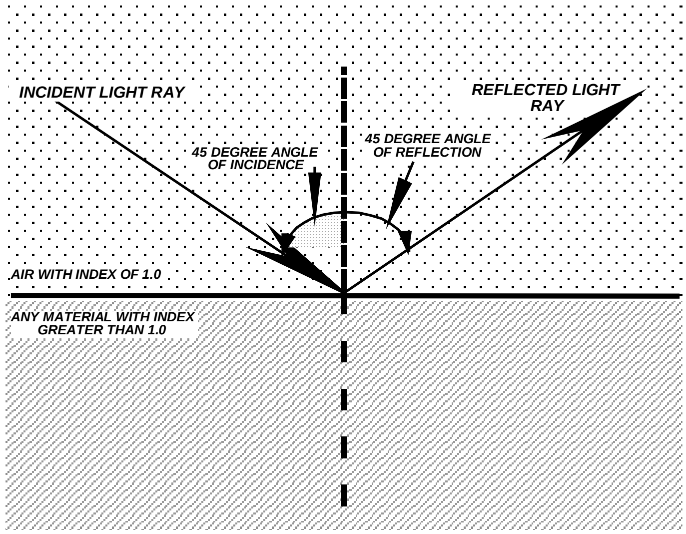


Figure 2.9: Angle of reflection

2.2.1.2 Total-Internal-Reflection

Now having the tools to understand how light behaves at an interface between two materials, a plot can be generated showing the angle of the transmitted light as the angle of the incident light is varied. Using Equation 2-6 choose an incident medium such as glass (n = 1.5), and a transmitted medium of air (n = 1.0), then:

$$\theta_t = \sin^{-1}\left(\frac{n_i}{n_t}\sin\theta_i\right) = \sin^{-1}\left(\frac{1.5}{1.0}\sin\theta_i\right) = \sin^{-1}(1.5\sin\theta_i) \qquad \textbf{(2-9)}$$

When [1.5 sin θ_i] has a value less than 1, there is no problem in obtaining a transmitted angle from Equation 2-9. However, when [1.5 sin θ_i] reaches the value of 1, the transmitted light has a value of 90 degrees. Then, as [1.5 sin θ_i] increases above 1, a real value cannot be computed for θ_t.

Setting [1.5 sin θ_i] equal to 1, and solving for θ_i, θ_i = 41.8 degrees. This often is referred to as the "critical angle of incidence" or just "critical angle" and is referred to as θ_{max} (the critical angle will be different for different materials). All light that is incident at angles greater than the critical angle will result in transmitted light angles that would exceed 90 degrees, if such were possible. Since this is impossible, then, *all of the light in this region must be reflected.*

This phenomenon can be represented graphically by varying the incidence angle from 0° to obtain the plot seen in Figure 2.10. As the critical angle of incidence is approached, the angle of the transmitted light approaches 90 degrees. At the critical angle, none of the incident light is transmitted! And, for light incident at all angles greater than 41.8 degrees, no light is transmitted. (This neglects the consideration for polarized light, which requires a more complex treatment.) Since no light is transmitted, all light is assumed to be reflected (Figure 2.11), hence the term 'total-internal-reflection':

$$R = 1 - T$$

$R = 1 - 0 = 1$, for all light incident above the critical angle.

This principle aids in the understanding of how optical fibers 'guide' light. (The graph in Figure 2.10 is unique for the transition between materials that have a ratio of 1.5 for their indices of refraction. Any other ratio will result in a different critical angle and resultant plot.).

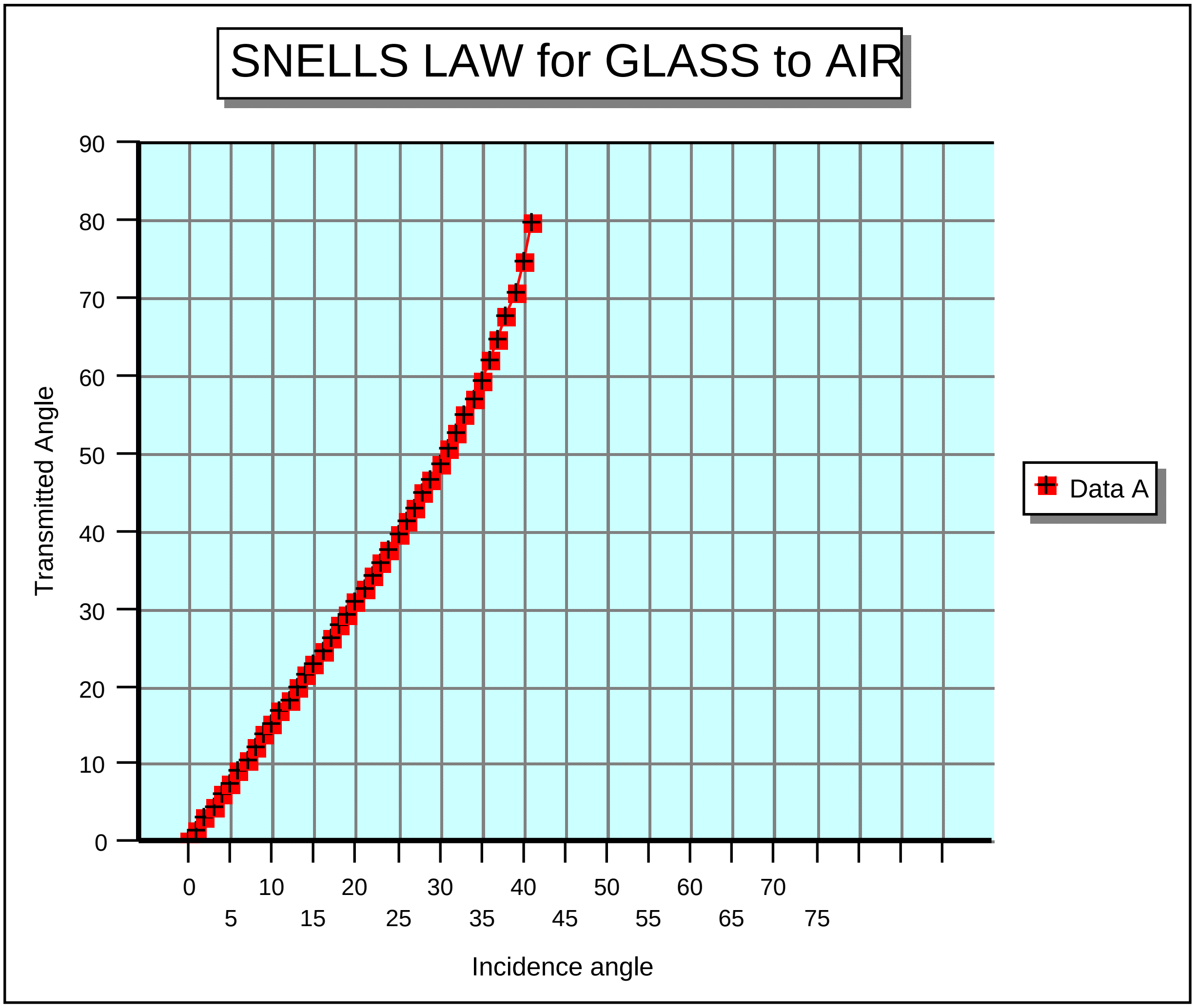


Figure 2.10: Snell's law for glass to air

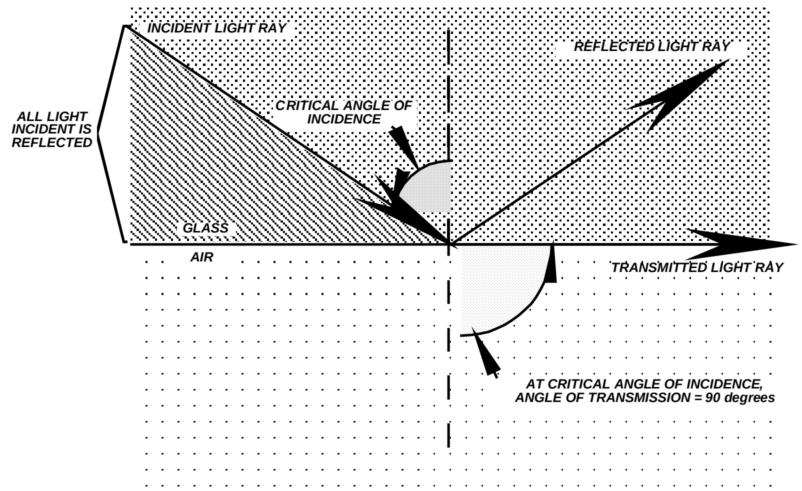


Figure 2.11: Total internal reflection for glass to air

2.2.1.3 Fresnel Reflection

Fresnel reflection is extremely important in all fiber optic systems. Practically speaking, whenever there is a discrete change in the index of refraction, some portion of light incident on the "discontinuity" will be reflected. The amount of light reflected varies, depending on the difference between the indices of refraction, and the polarization components of the light. Neglecting polarization, and focusing only on the power, the reflection coefficient of light reflected from a *normally incident* ray is given by:

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2} \qquad \textbf{(2-10)}$$

Here, n_1 is the index for the incident material, while n_2 is the index for the transmitted material. For the simple case of light in air (n = 1) incident on glass (n = 1.5), the reflection coefficient is 0.04. Then the transmitted light T, T = 1 - R, is 96% of the incident light with 4% of the light being reflected.

Light reflection is very important in fiber systems for many different reasons. One important reason occurs when utilizing lasers. Optical energy that is "fed back" into the laser can cause the laser-output-power to fluctuate, among other possible effects. Therefore, it is important when using lasers, to try to minimize any such effects.

Another important feature of reflection in fiber systems occurs when using an Optical Time Domain Reflectometer ("OTDR"), an instrument which is vital to troubleshooting fiber optic systems, and useful in certain fiber multiplexing techniques for "smart structures" (*Kersey*). OTDR's primarily operate on light that is reflected from components throughout the fiber system. Each component that reflects light does so in an individual manner, thereby providing it's own unique signature as well as for the system.

Still another important consideration of reflectivity is the loss of light through the system. While 4% is not a large amount of light, if a system had a dozen connectors, 3 or 4 switches, a variable attenuator, wavelength multiplexer and de-multiplexer, all with 4% reflection loss in addition to losses through the components, considerable light could be lost in a system.

There are many methods and techniques in common use to minimize reflection losses within fiber systems. Such methods include index matching gel, angled-cleaves and connectors, offset launching, and polarization-selection techniques when operating with lasers and singlemode fibers.

2.2.2 Concepts of Guided Light

Now apply what has been developed from the physics of light at an interface between two materials, to optical fiber, which has a unique geometric structure. The structure of fiber, while essentially a simple cylinder, requires very complex mathematics and physics to provide complete descriptions of light propagation (*Marcuse*). Such treatments are unnecessary here. Therefore, the discussion following is primarily qualitative, and utilizes elementary relationships, where useful, to enhance understanding.

2.2.2.1 Fiber Structure

The basic fiber structure needed to guide light consists of a core surrounded by a cladding (Figure 2.12). The index of refraction of the core, being greater than the index of refraction of the cladding, makes total-internal-reflection possible. Therefore, certain light ‘rays’ will remain inside the fiber, as long as they meet the critical angle criteria. Typical communications-grade optical fibers appear as long strands of glass material, usually less than 100 microns in core diameter. Plastic fibers with core diameters to 2mm have begun to be utilized for certain short distance applications (< 500 meters). More will be discussed about fiber types and specifications in following sections.

2.2.2.1.1 Core

Several different fiber configurations will be presented here, however the principle behind all fiber configurations is the same: a core material with an index of refraction greater than the cladding material. A typical plot of the index of refraction for a “step index” fiber is shown in Figure 2.13. Common communications grade fibers usually have a core index of refraction of anywhere from 1.450 to 1.480, however this parameter can be varied enormously and, adjusted with great accuracy (1 part in 10,000) if necessary. The application for such control of this parameter is discussed in the Numerical Aperture Section.

2.2.2.1.2 Cladding

Without a cladding, the core would be "immersed in air", which has an index of refraction of about 1.0. Therefore, the critical angle of incidence would be close to the 41.8 degrees used in the example. In optical fibers however, it has been found that a much greater critical angle is desirable, (see Numerical Aperture section). In order to provide better insight into what happens in the fiber, look at a cladding index of 1.470 and a core index of 1.475 This results in a core-cladding difference of only 0.005, which yields a critical angle of about 85 degrees (Figure 2.13)**.**

Core and cladding diameters usually are specified together, for example, "100/140" refers to a fiber that has a core diameter of 100 microns and cladding diameter of 140 microns. Some fiber sizes manufactured in large quantities include; 10/125, 50/125, 62.5/125, 85/125, 100/140. Many other fibers with sizes different than these have been fabricated for many different applications, and, unique fibers can be acquired from a number of manufacturers.

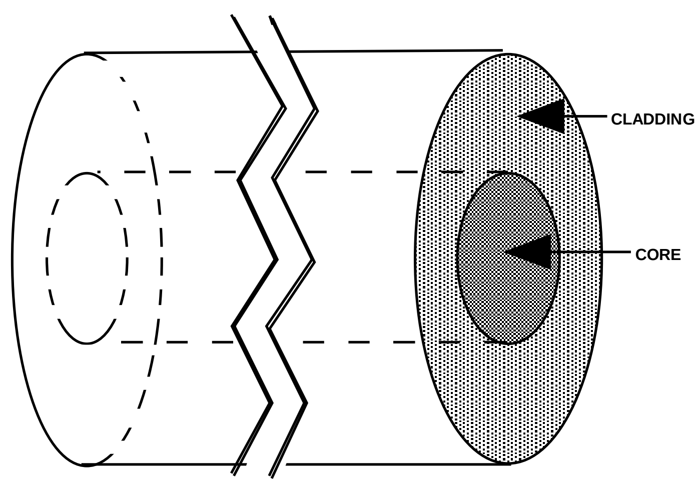


Figure 2.12: Basic fiber structure

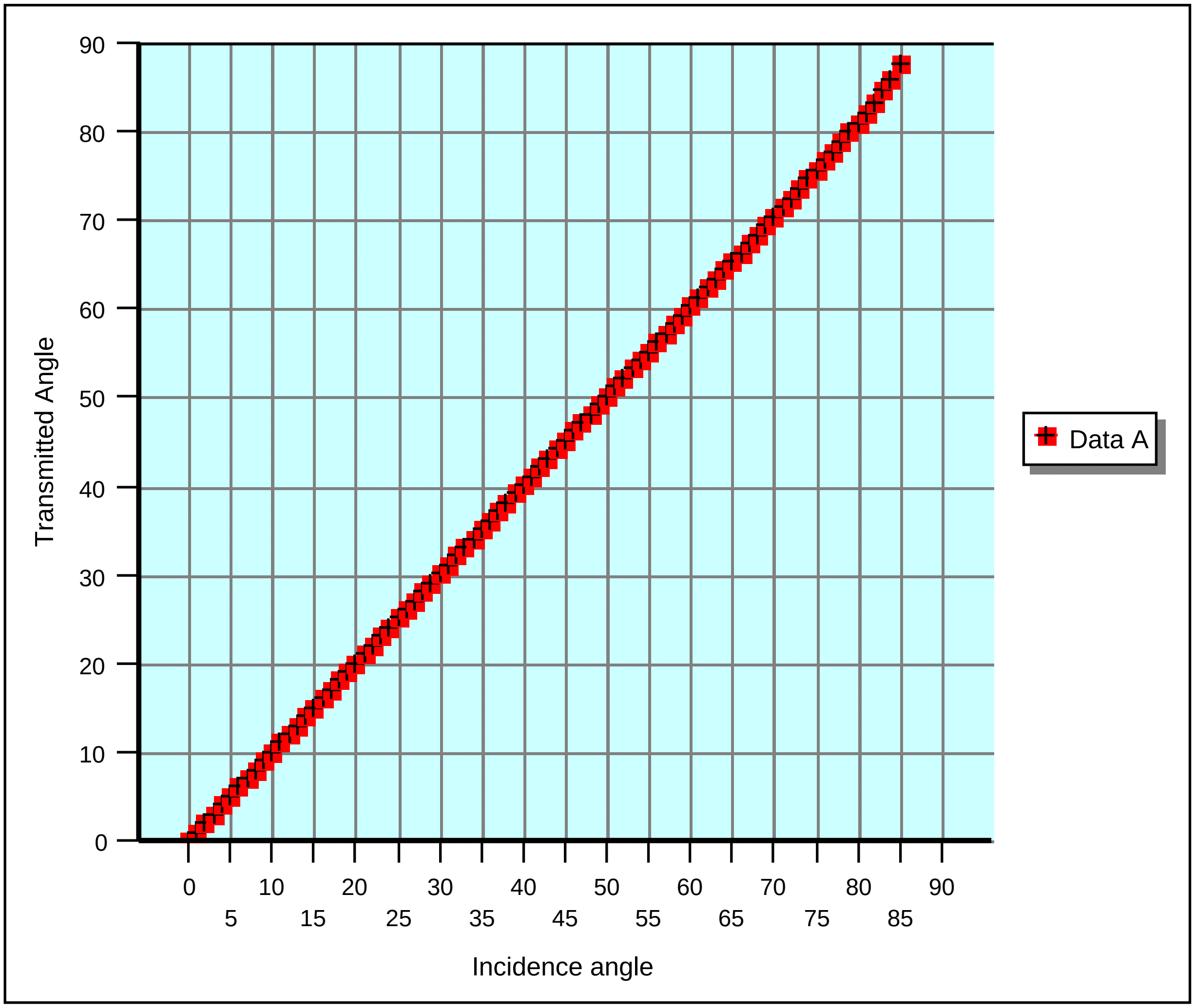


Figure 2.13: Snell's law example for fiber (Ni/Nt = 1.003)

2.2.2.1.3 Coatings, Jackets, and Cabling

An optical fiber consisting only of core and cladding is extremely fragile and is subject to degradation from external transverse forces, as well as chemical attack. To protect the fiber, many types of coatings are available that may be applied over the cladding. Depending on the application, several coatings may be applied one on top of another. These coatings range from the consistency of hardened epoxy to soft rubber-like plastics or composite materials and even metals (*Miller*). Some are very hard and do not easily cut with a razor blade, while the softer materials may be almost peeled off, once a cut is made.

While coatings are extremely important for protecting fiber, nearly all working-requirements with fiber necessitate removing the coating(s). This operation can be fairly challenging, and requires experience with fibers, knowledge of the coating materials, and the proper tools. Some hazard exists when working with glass fibers, since the fiber can be easily broken with improper handling, resulting in fiber fragments breaking off. **These fiber fragments are <u>dangerous</u>, and should be treated as if they were glass 'needles'. They can pierce the skin and break off like splinters, becoming extremely painful and difficult or impossible to remove. This hazard is greatest after the coating has been removed, and the fibers may be practically invisible, due to their small size. An untrained person should never attempt to work with fiber.**

Fiber coatings may be covered with "jackets", that could consist of any type of material typically found on electrical wires, ranging from simple plastic sheathes to Kevlar fabric to gold and aluminum. (Occasionally, the terminology "coating" and "jacket" are used interchangeably and may refer to the same material.) The majority of optical fiber is designed and developed for communications applications; hence the fiber usually is in cable form. Cables must be pulled from one location to the other, so considerable forces are used during cable installation. For that reason, many optical fiber cables have additional "strength members" included. Such strength members may be steel strands or if weight reduction is important, continuous Kevlar thread may be used.

Optical fiber cables with strength sufficient for resisting ocean environments are now common, as well as tactical-battlefield-specified cables, which must be able to withstand forces imparted from vehicles such as tanks. Cables for remotely controlled missiles also have been developed, which requires strength members that can survive enormous accelerations, stresses, and strains. From these examples, it is clear that cabling requirements vary enormously, yet in all situations, optical fiber cable has been successfully manufactured.

2.2.2.2 Fiber as a Waveguide

Getting the largest number of photons from point A to point B often is the bottom line for optical fibers used in communications. (However, for many fiber sensors, or certain high-speed applications, this is not always of great importance.) Therefore, the development of high-grade optical fiber has been extremely challenging. Perhaps the greatest of these challenges is due to the small fiber size. The necessity for the small size is in part due to the properties required for "electromagnetic waveguides". As mentioned earlier, the mathematical development of the waveguide model is beyond the scope of this report. However, a few important properties of fiber as a waveguide, are important to understanding and working with fibers, and include numerical aperture, modes, and their resultant effects on fiber applications and performance.

2.2.2.2.1 Step Index Fiber

A step index fiber has already been seen in previous examples. This is the simplest fiber type, in which the index of refraction of the core is constant. (Later, graded index fibers will be presented, in which the index of refraction of the core is varied.) Fabrication of step index fiber is less challenging than for graded index fiber, hence it was the first and was the most common multimode fiber type.

2.2.2.2.1.1. Numerical Aperture

Once light has entered the fiber, it is guided by the critical angle relationships previously shown. Now, these relationships also can be used to determine how much light may be injected into the fiber from a source such as a laser or light emitting diode. The result also describes the “output-transmission cone”, for light leaving the fiber. The "acceptance cone" defines how much light can enter the fiber (as well as exiting the fiber), and is referred to as the numerical aperture ("NA")(Figure 2.14). For step index fiber the NA is mathematically defined as:

$$NA = \sin\theta_{\max} = \left(n_{core}^2 - n_{clad}^2\right)^{\frac{1}{2}} \qquad \textbf{(2-11)}$$

It now should be apparent that varying the core and cladding indices of refraction has a significant impact on the numerical aperture of the fiber. A typical communications grade fiber has a numerical aperture of about 0.2. Plastic fibers have been fabricated with NA’s greater than 0.5. Light that enters the fiber within the NA will satisfy the critical angle requirement and remain in the fiber core.

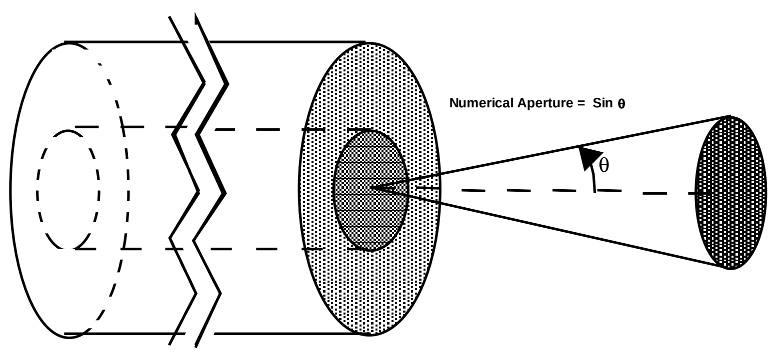


Figure 2.14: Numerical aperture

Some light may enter the core at a higher angle than defined by the NA. A fraction of this light is transmitted to the cladding, however some also is reflected. At the next reflection more is transmitted into the cladding and again some is reflected; this all occurs even though the critical angle requirement is not met. Therefore, near the launch location, all of the light in the core may not be "bound" to the core, and eventually will "leak" out. This will be discussed further in later sections.

2.2.2.2.1.2. Modes and multimode fiber

The ray model will be used for this discussion, since fiber is a waveguide, and the wave model provides for more accurate computation of modal properties. (For a large number of sensor applications, accurate computation of modal properties is unnecessary.) Modal properties can have enormous impact on the performance These impacts occur in areas of power measurement, interfacing fiber to instruments, connectorizing, splicing, bending, and using fiber in extreme environments (temperature, shock, vibration, humidity, vacuum, gasses, etc.).

A relationship exists between core diameter, wavelength, and modal content, known as the "V-Number" or normalized frequency (*Powers*):

$$V = \frac{2\pi d}{\lambda}\left(n_{core}^2 - n_{clad}^2\right)^{\frac{1}{2}} \quad \textbf{(2-12)}$$

The importance of this relationship lies primarily in it's bringing together the wavelength of light (λ), the diameter (d) of the fiber, and the indices of refraction of the core and the cladding. This information will be used in later sections to support explanations of the important parameters and characteristics of fibers.

2.2.2.2.1.2.1. Core Modes

In step index fiber, only light rays that are within the NA of the fiber will remain bound in the core of the fiber. Therefore, each light ray incident on the core that satisfies this requirement may be considered a unique "mode" injected into the fiber, Figure 2.15. (However, the waveguide model predicts mathematically, that only specific rays [angles] can be sustained within the fiber. Light rays at each of these specific angles is a true "mode". This results from the solutions of the electromagnetic waveguide equations.) Modes of light injected at the maximum NA angle are referred to as 'high-order modes", while light injected almost parallel to the axis of the fiber results in 'low-order modes'. High-order modes are more likely to scatter into the cladding and be lost, while low-order modes are more tightly bound to the core. Light that is perfectly parallel to the fiber axis sometimes is referred to as the 'zero-order mode'.

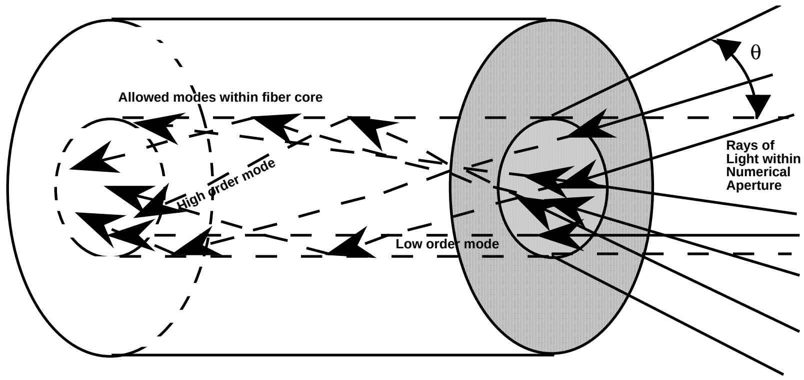


Figure 2.15: Rays representing modes in step index fiber

When light is first injected into the fiber, it may “overfill” the NA, with rays at angles above the NA, Figure 2.16. A portion of this light may internally reflect while some of it may be lost into the cladding. Eventually however, any light that does not satisfy the critical angle requirement within the fiber, will be lost, mostly into the cladding. At some distance down the fiber, when this condition is met, it is referred to as having an “Equilibrium Mode Distribution”. This means that light is essentially uniformly distributed among all the allowed modes in the fiber. Among other things, this condition allows for the most accurate measurement of power leaving the fiber. It also is important for enabling the optimum bandwidth utilization in communications applications.

2.2.2.2.1.2.2. Cladding Modes

It is possible that light will enter the fiber cladding from the end of the fiber, from the side of the fiber, or from the core (in which light does not meet the NA requirement). Since material outside the cladding will have a different index of refraction, some light will reflect at the cladding-edge boundary, as well as the cladding-core boundary, Figure 2.17. Such light has been known to propagate several meters in the cladding before being ejected, absorbed, or even launched back into the core. Most current fiber designs incorporate a coating with an index of refraction that is close to that of the cladding, thereby enhancing the loss of light from the cladding. Even with this design however, short-haul fiber links may carry some light in the cladding, which could negatively impact system performance.

2.2.2.2.1.2.3. Modal Distortion

Understanding that there are different modes represented as rays at different angles in the fiber, leads to an important consideration for communications applications, or sensor applications that utilize high frequency modulation. This is the concept of modal distortion, which refers to the distortion of the temporal characteristics of an input pulse due to the different transit times of different modes through the fiber, Figure 2.18.

From this figure it is easy to see that higher order modes must travel a longer path than low order modes. If a fiber is very long, then the low-order-mode from a given pulse will arrive at the exit before the high order mode arrives. Therefore, the pulse will spread out as it propagates through the fiber, Figure 2.19. For digital information, such spreading could lead to overlap of pulses, resulting in misinterpretation of bits, bytes, and words.

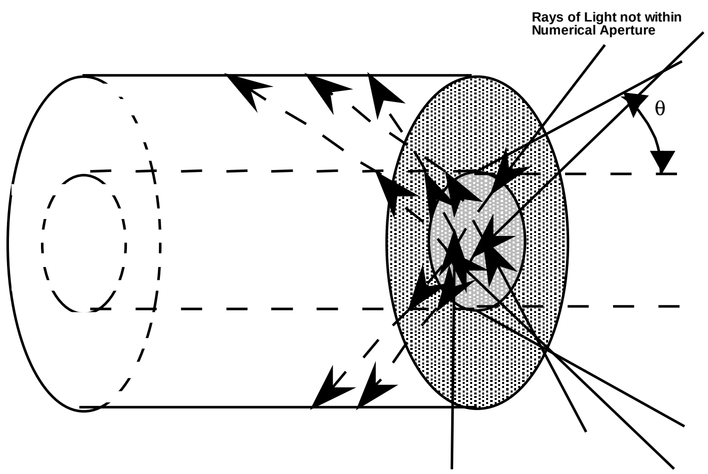


Figure 2.16: Overfill of numerical aperture

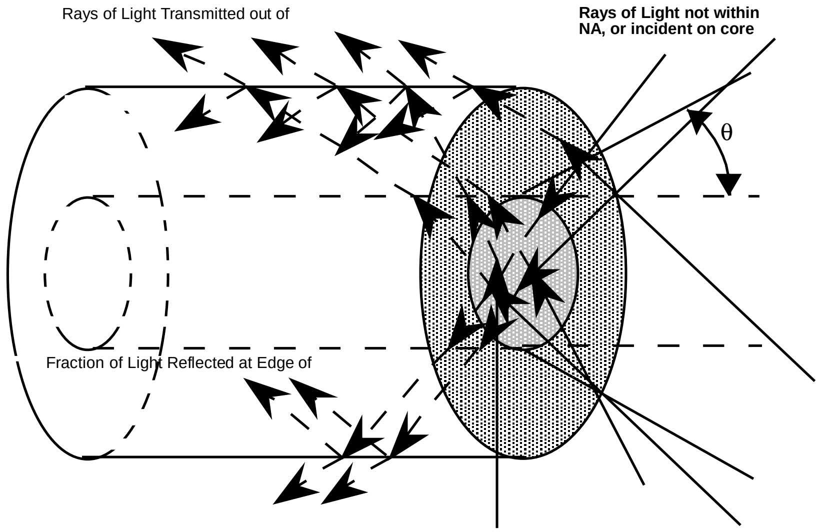


Figure 2.17: Cladding modes

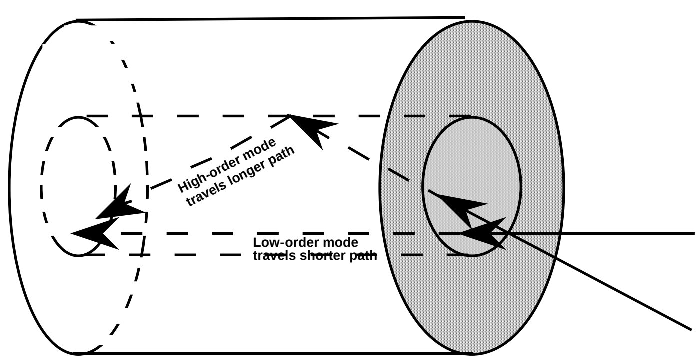


Figure 2.18: Mode paths through step-index fiber

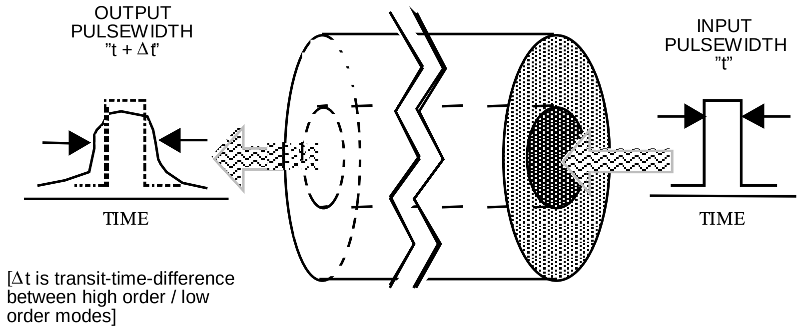


Figure 2.19: Pulse spreading from modes

2.2.2.2.1.2.4. Singlemode Fiber

Singlemode fiber is extremely important for the highest bandwidth, longest length communications applications, as well as interferometric sensor applications. Singlemode fiber is typically step-index fiber, with a very small core diameter when compared to multimode fiber. In order to obtain singlemode propagation, it is necessary that the wavelength of light and the diameter of the fiber maintain a unique relationship. That relationship is determined when the normalized frequency is less than 2.405:

$$V = \frac{2\pi d}{\lambda}\left(n_{core}^2 - n_{clad}^2\right)^{\frac{1}{2}} < 2.405 \qquad \textbf{(2-13)}$$

Choosing a wavelength of 1.31 microns, core and cladding indices of refraction of 1.475 and 1.474 results in:

$$d < \frac{2.405}{\frac{2\pi}{1.31\times10^{-6}}\left(1.475^2 - 1.474^2\right)^{\frac{1}{2}}} = 9.2 \;\; microns$$

The current most popular singlemode fiber for communications applications is designed for singlemode operation at 1.31 microns, with the core diameter of about 9 microns. However, there are possible advantages over this design, with fibers operating at 1.55 microns, which will be mentioned in following sections.

In singlemode operation, the "single" mode may consist of two different polarizations. It is possible to obtain fiber that will only allow 1 polarization to propagate. Such polarization-preserving fiber is true singlemode, and very important in some sensor applications.

2.2.2.2.1.3. Dispersion

It was mentioned earlier that the temporal profile of an optical pulse launched into a multimode fiber would undergo modal distortion as it travels down the fiber. The longer the fiber is, the more the amount of modal distortion. By utilizing singlemode fiber, modal distortion is minimized, resulting in longer transmission distances. However, there is a phenomenon that both singlemode and multimode fibers are subject to; chromatic, or material, dispersion.

Chromatic dispersion refers to the wavelength dependence of the index of refraction. Since the index of refraction determines the velocity of light in a material (Equation 2-4), different wavelengths will have different velocities in the fiber. (This is the same principle by which a prism splits white light into it’s components.) As a result, if light that is truly one color, i.e., “monochromatic” is launched into fiber, no dispersion will occur. Contrarily, if light is polychromatic (has a continuum of wavelengths), Figure 2.20, then the different wavelengths will travel at different velocities, resulting in a temporal spreading of the optical pulse. This spreading is similar to the modal distortion of a pulse shown in Figure 2.19.

A property known as waveguide dispersion also exists that is important in singlemode fibers. By combining the effects of material dispersion with waveguide dispersion, it is possible to fabricate fibers in which the total dispersion is theoretically zero at certain specified wavelengths, Figure 2.21 (*Allard*). For communications applications this is an exceptional performance enhancer (although it is not *perfectly* achievable in practice), it can be used with excellent practical benefits. The effects of dispersion are of greatest importance for very high frequency applications in communications, and/or very long distance applications of any kind. Currently, few sensor applications need be concerned about dispersion effects, unless broad-spectrum light sources are utilized.

2.2.2.2.2 Graded Index Fiber

Graded index optical fiber has been developed to reduce the amount of modal distortion inherent with step-index fiber. Whereas step index fiber has a uniform index of refraction across the core, the index of refraction for graded index fiber varies from the center of the core out to the cladding, Figure 2.22. One model for this design is to imagine several discrete layers of material, each with an index of refraction slightly less than the one closer to the core, Figure 2.23. As higher-order modes encounter each of these layers, it is refracted according to Snell’s law, and the transmitted light is “bent” slightly, Figure 2.24. Additionally, as the light approaches the core-cladding interface, where the index of refraction is lower than at the core, its velocity must increase, according to Equation 1-4.

Upon reflection at the core-cladding interface, the light is directed back towards the center of the fiber, where at each “layer” it is again refracted, and begins to slow down. When it reaches the axis of the fiber core, it will be traveling with the same velocity as the zero order mode, but in a “crossing” trajectory. The result of this design, is that the transit time through the fiber of higher order modes is much closer to the transit time of low order modes, thus reducing modal distortion.

Graded index fiber is extensively used in communications, with the dominant fiber being 62.5 micron core diameter with 125 micron cladding diameter.

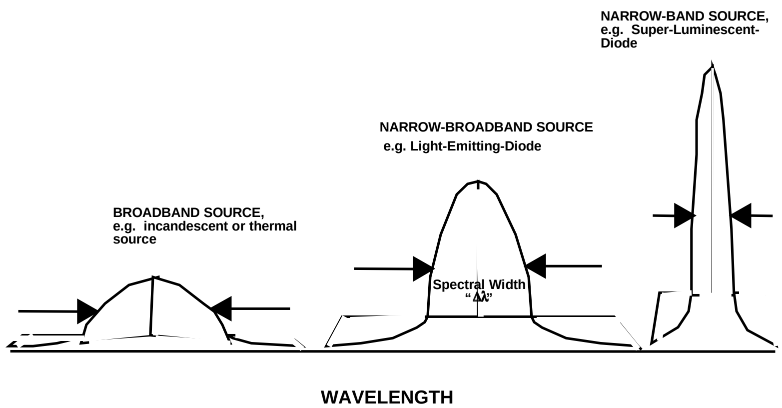


Figure 2.20: Examples of polychromatic spectra

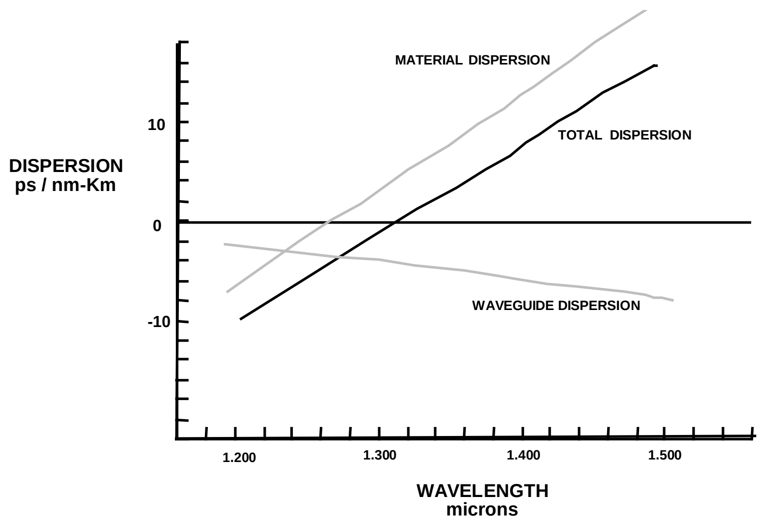


Figure 2.21: Material and waveguide dispersion for glass fiber

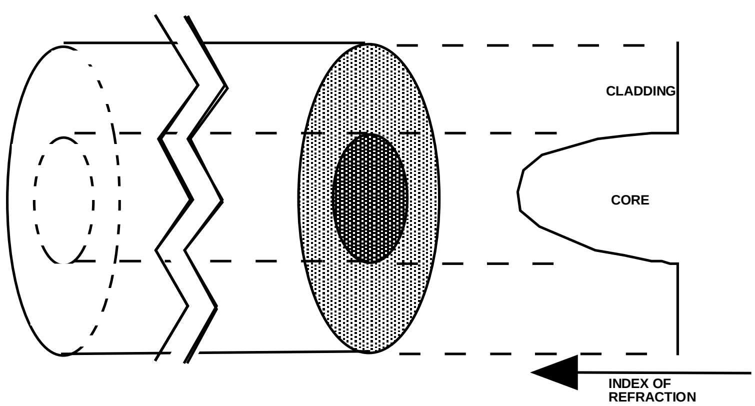


Figure 2.22: Profile of index of refraction for graded-index fiber

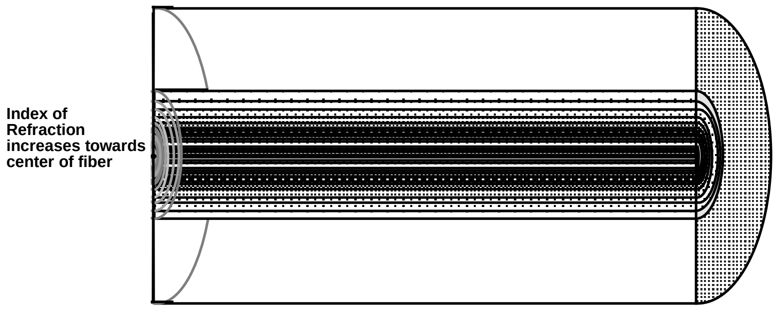


Figure 2.23: Model depicting layers of different indices of refraction for graded-index fiber

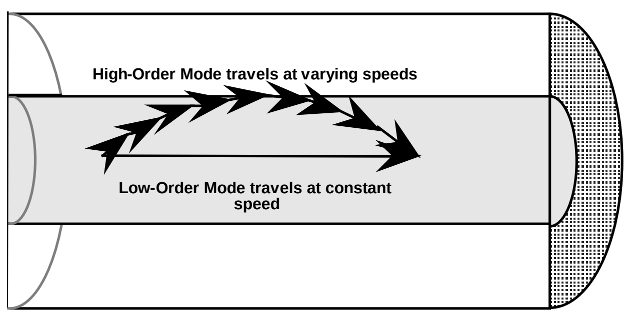


Figure 2.24: Modes propagating in graded-index fiber

2.2.2.3 Losses in Fiber

An extremely important consideration for nearly all fiber applications is the loss, or "attenuation" of light within the fiber. While glass fiber losses are much less than losses in wire or metallic waveguides, they are not negligible, and must be considered for nearly every system, except those that are very short in length as well as those operating at high-loss wavelengths. Plastic fiber losses may be significant, resulting in a limited range of application. Specialty fibers may have considerable losses, since they are optimized for performance in unique areas; and as a tradeoff, may end up being highly attenuating.

Fiber attenuation generally is measured in “decibels/kilometer”, and, optical power (P_o) usually is measured in dB_m. A level of 0 dB_m is equal to 1 milliwatt, while 10 dB_m is 10 milliwatts, and 20 dB_m is 100 milliwatts. Formally:

$$P_o\left(dB_m\right) = 10\log\frac{P(milliwatts)}{1.0(milliwatt)} \tag{2-14}$$

As a result, one microwatt of energy would be -30 dB_m and one nanowatt would be -60 dB_m. This scale is advantageous when dealing with optical power since power levels throughout fiber systems may vary by many orders of magnitude. For example, if fiber attenuation is 3 dB/km at the wavelength used, the fiber length is 10 km, and the light level launched into the fiber is 3 dB_m, the output light level would be -27 dB_m, or about 2 microwatts.

2.2.2.3.1 Wavelength Dependence

Figure 2.25 provides a typical loss profile for silica glass fibers (*Hoss*). It can be seen from this profile, that at 1.31 microns, a low level of attenuation is obtained. Beyond 1.31 microns, attenuation immediately increases until a wavelength of about 1.55 microns is reached, where the loss is less than at 1.31 microns. After about 1.6 microns, attenuation increases considerably. Due to this characteristic and the low dispersion near 1.31 microns, this wavelength currently is the most common for long distance communications.

2.2.2.3.2 Absorption and Scattering

Losses occur primarily from absorption and scattering of light. These losses are a result of imperfections in the fiber, contaminants, and inherent absorption properties of materials used to fabricate fiber. The dominant loss feature for silica glass fibers is known as Rayleigh scattering, which is a wavelength dependent phenomenon:

$$L_{Rayleigh} = \frac{A}{\lambda^4} \tag{2-15}$$

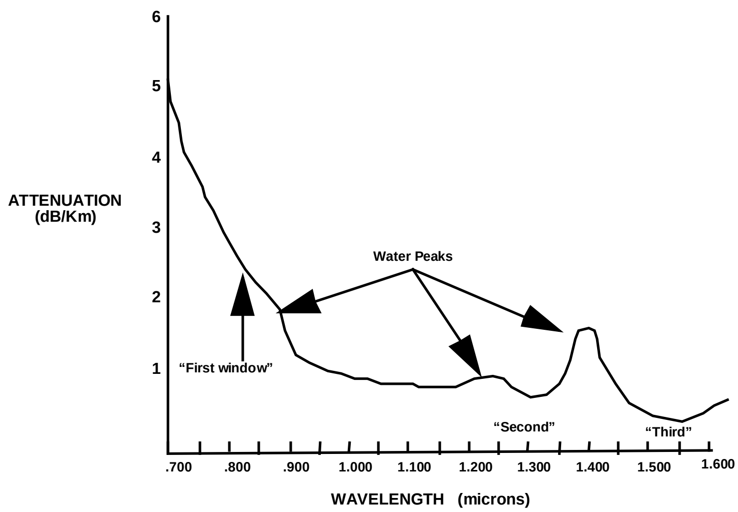


Figure 2.25: Attenuation vs. wavelength (single mode, glass fiber)

Here A is a constant that depends upon material composition. While other wavelength dependent losses exist, they typically are negligible compared to Rayleigh scattering in ordinary fibers. While Rayleigh scattering is from imperfections in the glass that are smaller than the wavelength of light, scattering also occurs from undesirable trace elements; molecules that entered the glass due to limitations of the technology to purify the fiber materials and the associated dopants. Absorption of light is inevitable: no perfect reflector exists. It is therefore not surprising that glass and the materials used in manufacturing will absorb some of the light. For silica-glass fiber, there are several absorption peaks that increase attenuation noticeably, as shown in Figure 2.25. These absorption bumps / peaks result from water trapped in the manufacturing process, resulting in formation of Si-OH (silicon-hydroxyl) in the fiber.

When fiber is manufactured, the process strives for the greatest possible control over reducing contaminants, and introducing dopants that increase performance. Some manufacturing methods immerse the fiber in gases that bond and extract some contaminants. Fiber manufacturing technology still is advancing steadily, and improvements in performance are ongoing.

2.2.2.3.3 Bending Losses

Losses due to bending in fiber can result in drastic changes in system performance, almost always degrading desired results (*Miller*). Bending effects may result in more light lost in the fiber, since they can "extract" higher order modes from the core into the cladding, where they are more likely to be lost. Normally, the potential for the greatest bending impact on power transmission occurs when utilizing multimode fiber in short-length applications. (In interferometric sensors, bending may cause drastic changes to system performance, although the affect is due more to impacts on polarization and phase.)

A great deal of analysis has been performed on bending impacts from both "small" radius bends (< 1cm), and bends less than about 5 cm. Bends greater than about 10 cm seldom have much impact on light propagation *Bends with less than a 5 cm radius should be avoided.*

2.2.2.3.4 Temperature, Modal Exchange, and Transient Attenuation

While modern fibers and fiber cables for communications are designed to minimize environmental effects, it is important to assume that environmental factors *will* have any impact on light propagating through fiber. The mechanisms by which temperature may influence light in fiber are extremely complex, and in some sensing techniques, the effect is so overwhelming as to render the system dysfunctional. Singlemode interferometric sensors are very susceptible to temperature effects while multimode, intensity based sensors are much less sensitive. One reason for the sensitivity in singlemode sensors is that the index of refraction is temperature dependent (temperature causes materials to expand and contract, thus resultant stresses and strains occur in the material thereby influencing the index of refraction, with a subsequent impact on the phase of the light).

In multimode fibers, the effect of temperature on the index of refraction may cause light in some modes to be converted to other modes. If more light is in higher order modes, it is more susceptible to being lost, since higher order modes are more loosely bound in the core. This could be especially degrading if bending losses are occurring at the same time as temperature extremes are being experienced. Note that these potential susceptibilities may be exploited for sensor applications.

Another phenomena known as transient attenuation can lead to system performance problems in multimode fibers. As discussed in earlier sections, light from higher order modes or poor launching conditions may couple into the cladding and under certain circumstances may stay in the cladding a short distance. If the power level is measured at the end of this short distance, and light from the cladding is included in the power measurement, then the measurement is not an accurate measurement of the amount of light in the core. Therefore, more power is perceived to be in the system than actually will be available. This "transient power" results in a higher attenuation than would be expected if only the light in the core of the fiber is measured. This situation is seldom of concern if fiber lengths are longer than 50 meters, although the phenomenon could exist for up to 500 meters under certain circumstances.

2.2.2.4 Fabrication and Types of Optical Fibers

Optical fibers are being fabricated from more materials than ever before. However, optical-grade silica-glass is still the predominant material for communications applications, as well as for most fibers for sensor applications. Silica-glass fibers are often doped with materials such as Germanium dioxide and Aluminum dioxide to provide improvements in performance through changing the index of refraction as well as other properties of the fiber.

Significant advances in the last decade have resulted in development of plastic fibers with performance sufficient for short distance communications applications (typically less than 500 meters, and bandwidths less than 200 MHz). Since communications' demand has resulted in increased fiber quality and decreased cost, a growing number of applications utilize plastic fibers whose cost is significantly reduced. One example of this is illumination-applications. Large-core plastic fibers ($\geq$ 500 microns) are able to transmit sufficient light to be considered for applications such as car-dash instruments, equipment-inspection light sources, and medical instrumentation. Such 'cold-light' sources have the benefit of illumination without significant heat, as well as non-electrical requirements to the point of illumination.

Special applications have necessitated development of unique fibers, including quartz, and materials such as Chalcogenides and Fluorides. Development of such fibers are usually driven by the necessity to transmit special optical wavelengths, such as Ultraviolet (< .4 micron), and Mid-Infrared (~2 micron - ~10 microns). While some fibers have been developed for carbon-dioxide lasers (10.6 micron wavelength), it is rare to find fibers designed to transmit longer wavelengths. Also, most special fibers for unique applications are very expensive and are difficult to work with. Compatible equipment and materials often does not exist, and the fiber is usually available in relatively short lengths.

A growing number of applications in special environments demand special fibers. Environments where there are extreme pressures, extreme temperatures, vacuum, and the interfaces between extreme environments require these fibers.

Radiation-hardened fibers are manufactured with special dopants in the glass and are pre-exposed to radiation for increased radiation resistance. Many military applications have rigid specifications for optical fibers relating to performance in high-radiation environments.

An interesting example of a unique fiber is one in which the fiber is doped with materials that fluoresce when irradiated with various light sources. Such fibers may find use in sensing applications ranging from the biomedical to the chemical manufacturing environment.

As the diversity of applications for fiber sensors steadily increases, unique fibers continue to be developed to satisfy unusual requirements.

2.2.2.5 Advantages of Optical Fibers

Why there are so many advantages to fiber is rooted in the physics of working with photons instead of working with electrons. Photons are electrically neutral: they do not carry a charge. Photons do not have a rest-mass, and, the mass of photons is negligible when compared to the mass of electrons. Inside a wire, electrons require a “push” (voltage) to overcome inertial and electromagnetic forces that “prefer” electrons stay where they are. A flow of electrons (current) generates heat in a wire, and the voltage always must be present or the electrons will stop flowing (neglecting superconductivity). A flow of electrons creates magnetic fields that extend beyond the boundaries of the wire. These magnetic fields may influence electrons traveling in other wires nearby, and, can create currents in the other wires. Also, wires can act as unwanted antennas, where electromagnetic radiation passing by the wire can stimulate a flow of electrons. Combining these possible effects can produce “crosstalk” between wires, which degrades performance. A worst case scenario is that metal wires actually attract lightning strikes, which is normally disastrous to equipment.

Photons do not have any of these conditions associated with their implementation in optical fiber. They do not create electric or magnetic fields that can influence other photons in other fibers, or, even in the same fiber. This effectively eliminates crosstalk.

Related to crosstalk between separate wires, is the inherent difficulty of using one wire to send signals in both directions at the same time. This concept is not practical with wires although it is fairly easily accomplished with fiber technology. This is due to the lack of interaction between adjacent photons traveling through the fiber, either in the same direction, or in opposite directions, whereas electrons repel each other due to their common electric charge.

Since photons (generally) do not interfere with each other, it is possible to combine an extra-ordinarily large number of signals onto a single fiber. In fact, compared to a wire, the potential is thousands of times greater. This technology is called wavelength division multiplexing (Figure 2.26), and is under aggressive implementation and advancement. Maximum utilization of fiber capacity typically includes this technique, where many independent signals are multiplexed onto a single fiber. Theoretically, hundreds of different wavelengths could be combined onto a single fiber, although practically, limits exist due to losses through the components.

Since no electrical signal is carried on the fiber, fiber is safer in environments such as those where explosive gases or fuels may be present. Any wire has some potential to produce a spark, even with advanced safety features. However, that potential truly is eliminated with proper use of optical fiber.

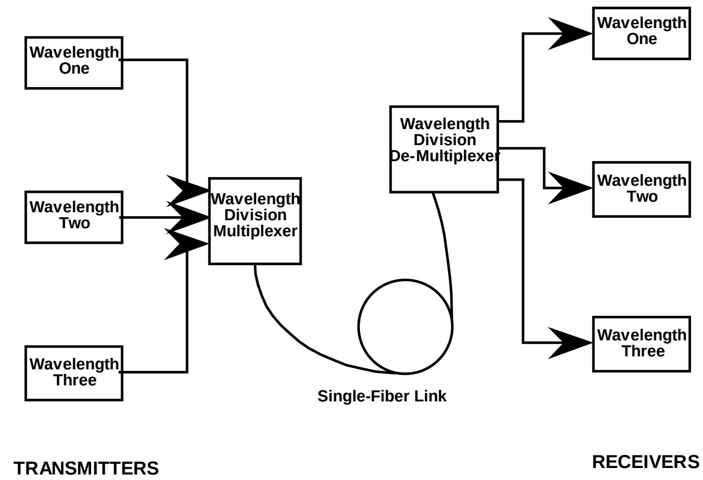


Figure 2.26: Wavelength division multiplexing

Electrical wires often are bundled together in cables by the dozens, hundreds, or even thousands, in high-density applications such as may be found in ships, submarines, airplanes, satellites, office buildings, trains, automobiles, manufacturing plants, scientific labs, trans-oceanic communications links, and anywhere communication or data is exchanged. Cables containing large numbers of metal wire can end up contributing extensive weight and volume to the application. In some applications, weight and volume are not critical, such as buried communications lines. However, for many applications, weight and volume can be extremely important, and minimizing these factors in any way is critical. One example with such importance is aircraft. Large aircraft may have a ton or two of wires installed, occupying considerable volume. If a 90% reduction in both weight and volume is possible, then many benefits may result. At the very least, the reduction in weight alone would improve fuel economy saving perhaps millions of gallons of fuel over the lifetime of the vehicle, and perhaps even tens of millions for a fleet. Similar benefits accrue when considering naval fleets and submarines.

These examples demonstrate just a few of the advantages to using fiber. Benefits such as geometric flexibility, footprint, increased sensitivity, increased performance, packaging advantages and more, are extensively discussed in (*Udd, 1991a; Kersey*).

2.2.2.6 Fiber Strength Characteristics

If optical fibers were too fragile and broke easily, they would not be finding such widespread implementation throughout the communications industry. While bare optical fiber indeed is fragile with respect to transverse (shear) forces, it has a very high axial strength. The major challenge with fiber could be protecting it from shear forces. Since glass is brittle and does not bend much, any surface crack, flaw, or nick on the surface of the fiber increases the probability of the fiber shearing. When developing new applications of fibers and fiber sensors, it is important to design in protection from shear forces. The exact demands, of course, depend upon the application, the fiber type, and the available fiber coatings and cables. Mechanical design analysis always should be performed to determine the maximum stresses on the fiber from the application and deployment, and appropriate specifications for the fiber, coating, and cabling should be generated.

2.2.2.7 Review of Critical Fiber Performance Parameters

While a thorough understanding of optical fibers can only be obtained through working with and studying the technology, a few essential items must be emphasized. It is prudent to review some of these items and stress their importance. Above all, these parameters must be the first items to be determined; neglecting any of these could lead to failure of the system.

2.2.2.7.1 Diameter / Mode Field Diameter

The core diameter of optical fibers plays an important role as far as determining modal characteristics for light propagation. Large core glass fibers (50 to 100 microns or larger) result in multimode operation for wavelengths in the visible and near infrared region. To obtain singlemode operation, the core must be reduced, and for the 1.31 micron window, a core diameter of about 8 or 9 microns is needed.

When dealing with singlemode fibers, (for reasons that require advanced mathematical treatment and are beyond the scope of this effort) it is more common to refer to the fiber's "mode-field diameter" (MFD), rather than the core diameter. Some of the energy actually is in the cladding, although most of the energy is in the core. So, the diameter within which all of the energy resides actually is greater than the physical diameter. Most manufacturers will specify MFD for singlemode fiber rather than core diameter.

Fiber diameter is a very important design parameter. To begin with, it differentiates between singlemode and multimode fiber. If the difference is not known, and singlemode fiber is obtained rather than multimode fiber, one of the first problems would be power launched. With a larger diameter and numerical aperture, orders of magnitude more power can be launched into multimode fiber. Next determine bandwidth. If bandwidth is the highest priority then singlemode fiber may be a necessity, thus resulting in a tradeoff with respect to power launched. One more example on the importance of diameter is in interferometric sensor application. In such applications, singlemode fiber is required.

When assembling fiber systems, it is not uncommon to be interfacing different fibers and components pigtailed with fiber from different manufacturers. Connectorizing and splicing fibers from different manufacturers is challenging enough; dealing with diameters that are mismatched by more than a few percent makes the process particularly inefficient. Always obtain specifications for the fiber diameter and as many fiber parameters as possible. Then, if unusual losses are experienced, analysis of the specifications may indicate poor matching of components, which results in inferior coupling of light.

2.2.2.7.2 Attenuation

Fiber attenuation is wavelength dependent, which can be especially important if a fiber system utilizes several different wavelengths. Manufacturers may provide either a spectral attenuation profile such as Figure 2.25, or the loss at the operating wavelength, in dB/km. When preparing a *system power budget*, especially for links that may be medium to long length or utilize wavelengths where loss is high, fiber attenuation must not be assumed negligible. If, for example, green LED's are used in a fiber link of 500 meters, the resultant loss due to the fiber alone could be 5 to 10 dB.

In multi-spectral systems, each wavelength may require an independent power-loss analysis. For example, wavelength multiplexed systems operating with 0.85 and 1.3 micron sources will experience completely different losses at each wavelength, not only in the fiber, but in many of the components as well. However, if the wavelengths are within about 0.01 microns of each other, the difference in attenuation could (possibly) be negligible.

2.2.2.7.3 Index Profile / Numerical Aperture

The main importance of index profile is for multimode fiber applications. The graded index profile provides much greater bandwidth than does step index fiber. For nearly all multimode communications applications, graded index fiber is the fiber of choice since it provides the greatest benefit. Currently, 62.5/125 fiber is the most popular size. The designation "GI" for graded index is common. While most all singlemode fiber is step index, graded index singlemode fiber has been fabricated and used in some special applications. Certainly graded index fiber provides increased bandwidth, however, if bandwidth is not a critical system parameter, then step index fiber typically is more cost-effective.

Numerical aperture is vital if fiber applications (especially sensor applications) are designed so that light exits and re-enters the fiber ("extrinsic" sensing) frequently. Since numerical aperture determines how much light will be accepted into the fiber and ultimately how much remains in the fiber, it is critical to match all external optical, mechanical, or opto-mechanical elements or assemblies with the numerical aperture to efficiently launch light into the fiber. This is not as important if utilizing pig-tailed components (components with a fiber permanently attached), but for most sensor applications transducers usually are not pigtailed.

Finally, as mentioned previously regarding fiber diameter, a very important reason for knowing numerical aperture occurs when interfacing pigtailed components from one manufacturer to fiber or components from another manufacturer. A few percent difference in numerical aperture probably is not very critical, however if the NA is off a few percent and the diameter is off a few percent, considerable losses may compound rapidly, especially if extrinsic sensors are implemented, or if the system is complex and contains many components.

2.2.2.7.4 Cutoff Wavelength

Cutoff wavelength has not been discussed previously, but it is mentioned here since it may be of great importance for high bandwidth and/or certain wavelength multiplexed systems. Also, a special class of fiber sensors known as “few mode sensors” require knowledge of the cutoff wavelength. Simply put, the cutoff wavelength is the wavelength above which, singlemode operation is guaranteed. For example, if the cutoff wavelength is 1.305 microns, then operation above that wavelength will result in singlemode operation. Conversely, if a wavelength less than the cutoff is used, multimode operation will result. This enables possible modal distortion that would dramatically impact high bandwidth systems. From Equation 2-12, the cutoff wavelength is obtained by setting the normalized frequency equal to 2.405, and solving for wavelength:

$$\lambda_{cutoff} = \frac{2.405 \quad 2\pi d}{\left(n_{core}^2 - n_{clad}^2\right)^{\frac{1}{2}}}$$

Usually sufficient "engineering margin" exists with cutoff wavelength such that careful specification of source wavelength is not absolutely critical. A condition exists however with certain lasers that might result in a singlemode system switching to a "few-mode" system. Some diode lasers shift their wavelength due to temperature changes or reflected light coupled back into the laser. If the wavelength shift is to a longer wavelength, then no problem will occur as far as singlemode propagation is concerned. However, if the shift is to a shorter wavelength and the shorter wavelength is below cutoff, the system could shift to more than one mode. Such shifting typically degrades performance dramatically. Such occurrences are not common, consequently, it is important to match the source type and specifications to the fiber, to minimize the probability of such occurrences.

2.2.2.7.5 Dispersion

Fiber dispersion usually is important only for very high bandwidth and/or long distance singlemode applications. It is not typically of concern in multimode systems, since modal distortion is a much greater influence.) If specified by the manufacturer, dispersion is given in picoseconds/nanometer-kilometer. For most fiber sensor applications, consideration of dispersion seldom is necessary.

For communications applications, the ultimate fiber would have minimum attenuation as well as zero (minimum) dispersion. However, zero dispersion occurs around 1.3 microns, while minimum attenuation occurs around 1.55 microns. Some effort has been invested, and systems have been fabricated, in which the fiber has been modified to shift the zero dispersion point to 1.55 microns through doping and careful manipulation of core index. These are known as “Dispersion Shifted fibers”. Unfortunately, the process for shifting dispersion results in an increase of attenuation, and the ideal goal has not been obtained. Research continues on these fibers, along with another approach known as “Dispersion Flattened fibers”. This approach attempts to produce zero dispersion over a range of wavelengths, or at a few specific wavelengths, such as both 1.3 and 1.55 microns. By combining these approaches with wavelength multiplexing of several lasers, single fibers have been able to transmit 1000’s of Gigabits per second of information over distances on the order of 50 to 100 km.

3.0 INTRODUCTION TO FIBER OPTIC SENSORS

Over the past twenty years, two major product revolutions have taken place due to the growth of the optoelectronics and fiber optic communications industries. The optoelectronics industry has brought about such products as compact disc players, laser printers, bar code scanners and laser pointers. The fiber optic communication industry has literally revolutionized the telecommunication industry by providing higher performance, more reliable telecommunication links with ever-decreasing bandwidth cost. This revolution is bringing about the benefits of high volume production to component users and a true information superhighway built of glass.

In parallel with these developments, fiber optic sensor technology has been a major user of technology associated with the optoelectronic and fiber optic communication industry (*Culshaw, 1988; Culshaw, 1989; Giallorenzi, 1982; Krohn, 1988; Udd, 1991a; Udd, 1992*). Many of the components associated with these industries were often developed for fiber optic sensor applications. Fiber optic sensor technology in turn has often been driven by the development and subsequent mass production of components to support these industries. As component prices have fallen and quality improvements have been made, the ability of fiber optic sensors to displace traditional sensors for rotation, acceleration, electric and magnetic field measurement, temperature, pressure, acoustics, vibration, linear and angular position, strain, humidity, viscosity, chemical measurements and a host of other sensor applications, has been enhanced. In the early days of fiber optic sensor technology, most commercially successful fiber optic sensors were squarely targeted at markets where existing sensor technology was marginal or in many cases nonexistent. The inherent advantages of fiber optic sensors which include their ability to be lightweight, of very small size, passive, low power, resistant to electromagnetic interference, high sensitivity, wide bandwidth and environmental ruggedness were heavily used to offset their major disadvantages of high cost and unfamiliarity to the end user.

The situation is changing. Laser diodes that cost $3000 in 1979 with lifetimes measured in hours now sell for a few dollars in small quantities, have reliability of tens of thousands of hours and are used widely in compact disc players, laser printers, laser pointers and bar code readers. Single mode optical fiber that cost $20/m in 1979 now costs less than $0.10/m with vastly improved optical and mechanical properties. Integrated optical devices that were not available in usable form at that time are now commonly used to support production models of fiber optic gyros. In addition, they could drop dramatically in price in the future while offering ever more sophisticated optical circuits. As these trends continue, the opportunities for fiber optic sensor designers to produce competitive products will increase and the technology can be expected to assume an ever more prominent position in the sensor marketplace. In the following sections the basic types of fiber optic sensors that are being developed will be briefly reviewed followed by a discussion of how these sensors are and will be applied.

3.1 BASIC CONCEPTS AND INTENSITY BASED FIBER OPTIC SENSORS

Fiber optic sensors are often loosely grouped into two basic classes referred to as extrinsic or hybrid fiber optic sensors, and intrinsic or all fiber sensors. Figure 3.1 illustrates the case of an extrinsic or hybrid fiber optic sensor.

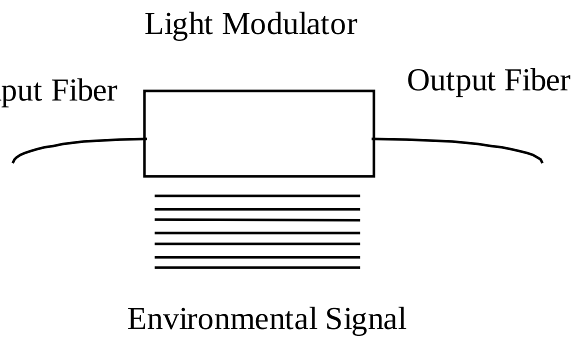


Figure 3.1: Extrinsic fiber optic sensors consist of optical fibers that lead up to and out of a "black box" that modulates the light beam passing through it in response to an environmental effect.

In this case an optical fiber leads up to a "black box" which impresses information onto the light beam in response to an environmental effect. The information could be impressed in terms of intensity, phase, frequency, polarization, spectral content or other methods. An optical fiber then carries the light with the environmentally impressed information back to an optical and/or electronic processor. In some cases, the input optical fiber also acts as the output fiber. The intrinsic or all fiber sensor shown in Figure 3.2 uses an optical fiber to carry the light beam and the environmental effect impresses information onto the light beam while it is in the fiber. Each of these classes of fibers in turn has many subclasses with, in some cases sub subclasses (*Udd, 1991a*) that consist of large numbers of fiber sensors.

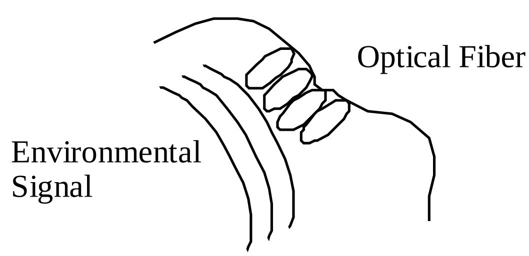


Figure 3.2: Intrinsic fiber optic sensors rely on the light beam propagating through the optical fiber being modulated by the environmental effect either directly or through environmentally induced optical path length changes in the fiber itself.

In some respects, the simplest type of fiber optic sensor is the hybrid type that is based on intensity modulation (*Lagokos, 1981; Yao, 1983*). Figure 3.3 shows a simple closure or vibration sensor that consist of two optical fibers that are held in close proximity to each other. Light is injected into one of the optical fibers and when it exits, the light expands into a cone of light whose angle depends on the difference between the index of refraction of the core and cladding of the optical fiber. The amount of light captured by the second optical fiber depends on its acceptance angle and the distance d between the optical fibers. When the distance d is modulated, it in turn results in an intensity modulation of the light captured.

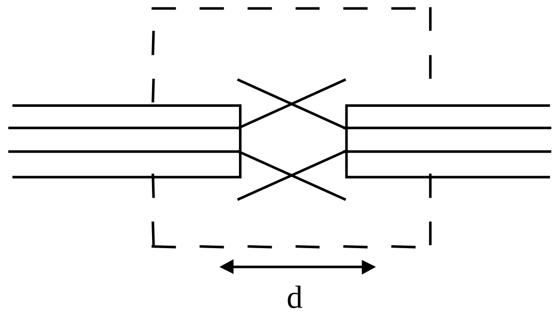


Figure 3.3: Closure and vibration fiber optic sensors based on numerical aperture can be used to support door closure indicators and measure levels of vibration in machinery.

A variation on this type of sensor is shown in Figure 3.4. Here a mirror is used that is flexibly mounted to respond to an external effect such as pressure. As the mirror position shifts the effective separation between the optical fibers shift with a resultant intensity modulation. These types of sensors are useful for such applications as door closures where a reflective strip, in combination with an optical fiber acting to input and catch the output reflected light, can be used.

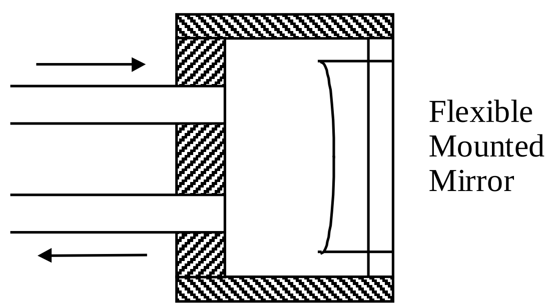


Figure 3.4: Numerical aperture fiber sensor based on a flexible mirror can be used to measure small vibrations and displacements.

By arranging two optical fibers in line, a simple translation sensor can be configured as in Figure 3.5. The output from the two detectors can be proportioned to determine the translational position of the input fiber.

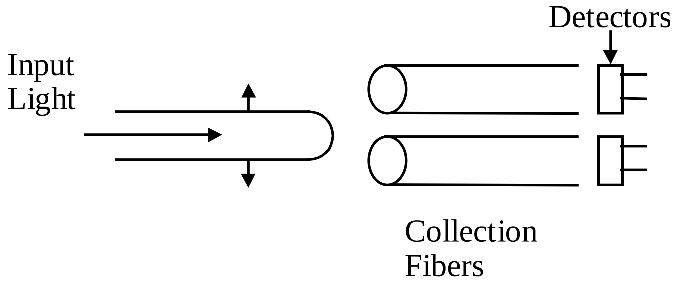


Figure 3.5: Fiber optic translation sensor based on numerical aperture uses the ratio of the output on the detectors to determine the position of the input fiber.

Several companies have developed rotary and linear fiber optic position sensors to support applications such as fly-by-light (*Udd, 1994*). These sensors attempt to eliminate electromagnetic interference susceptibility to improve safety, and to reduce shielding needs to reduce weight. Figure 3.6 shows a rotary position sensor (*Fritsch, 1989*) that consists of a code plate with variable reflectance patches placed so that each position has a unique code. A series of optical fibers are used to determine the presence or absence of a patch.

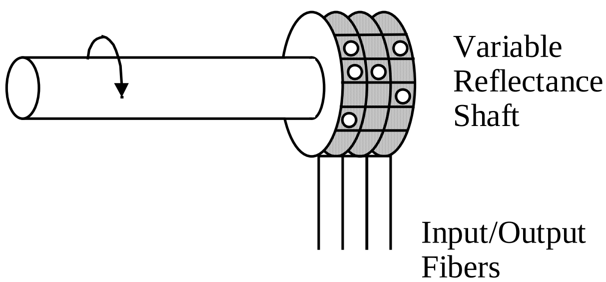


Figure 3.6: Fiber optic rotary position sensor based on reflectance used to measure rotational position of the shaft via the amount of light reflected from dark and light patches.

An example of a linear position sensor using wavelength division multiplexing (*Fritsch, 1986*) is illustrated by Figure 3.7. Here a broadband light source, which might be a light emitting diode, is used to couple light into the system. A single optical fiber is used to carry the light beam up to a wavelength division multiplexing (WDM) element that splits the light into separate fibers that are used to interrogate the encoder card and determine linear position. The boxes on the card of Figure 3.7 represent highly reflective patches while the rest of the card has low reflectance. The reflected signals are then recombined and separated out by a second wavelength division multiplexing element so that each interrogating fiber signal is read out by a separate detector.

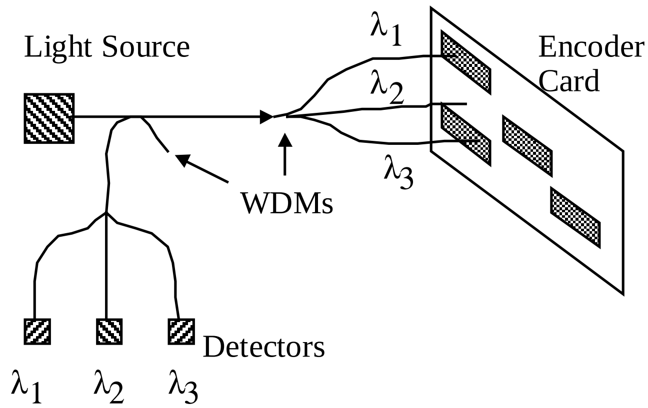


Figure 3.7: Linear position sensor using wavelength division multiplexing decodes position by measuring the presence or absence of reflective patch at each fiber position as the card slides by via independent wavelength separated detectors.

A second common method of interrogating a position sensor using a single optical fiber is to use time division multiplexing methods (*Varshneya, 1987*). In Figure 3.8, a light source is pulsed. The light pulse then propagates down the optical fiber and is split into multiple interrogating fibers. Each of these fibers is arranged so that they have delay lines that separate the return signal from the encoder plate by a time that is longer than the pulse duration. When the returned signals are recombined onto the detector the net result is an encoded signal burst corresponding to the position of the encoded card.

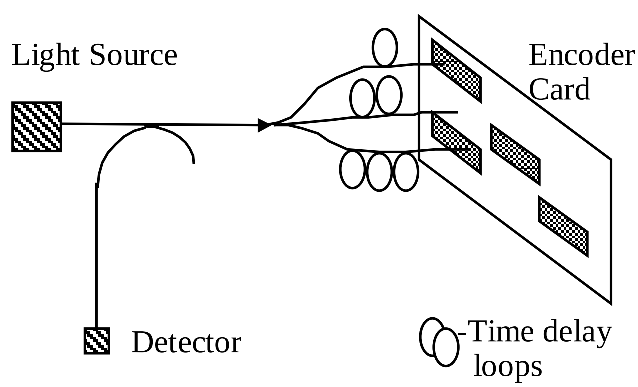


Figure 3.8: Linear position sensor using time division multiplexing measure decodes card position via a digital stream of on's and off's dictated by the presence or absence of a reflective patch.

These sensors have been used to support tests on military and commercial aircraft that have demonstrated performance comparable to conventional electrical position sensors used for rudder, flap and throttle position (*Udd, 1994*). The principal advantages of the fiber position sensors are immunity to electromagnetic interference and overall weight savings.

Another class of intensity based fiber optic sensors is based on the principle of total internal reflection. In the case of the sensor in Figure 3.9, light propagates down the fiber core and hits the angled end of the fiber. If the medium into which the angled end of the fiber is placed has a low enough index of refraction then virtually all the light is reflected when it hits the mirrored surface and returns via the fiber. If however the index of refraction of the medium starts to approach that of the glass some of the light propagates out of the optical fiber and is lost resulting in an intensity modulation.

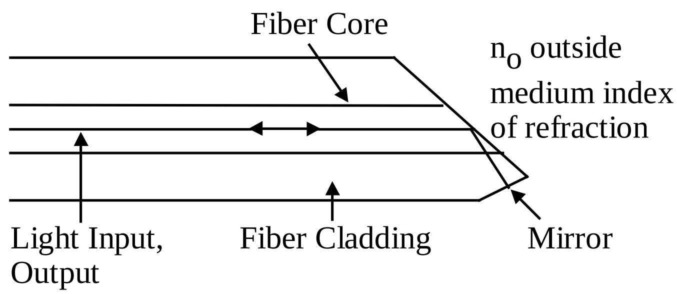


Figure 3.9: Fiber sensor using critical angle properties of a fiber for pressure/index of refraction measurement via measurements of the light reflected back into the fiber.

This type of sensor can be used for low-resolution measurement of pressure or index of refraction changes in a liquid or gel with one to ten percent accuracy. Variations on this method have also been used to measure liquid level (*Snow, 1983*) as shown by the probe configuration of Figure 3.10. When the liquid level hits the reflecting prism, the light leaks into the liquid, greatly attenuating the signal.

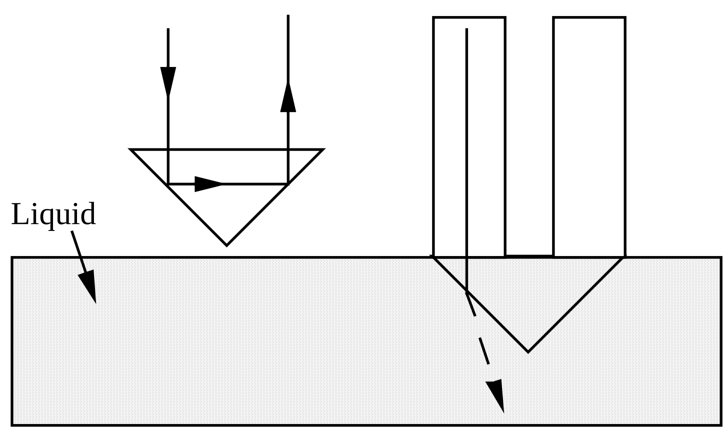


Figure 3.10: Liquid level sensor based on total internal reflection detects the presence or absence of liquid by the presence or absence of a return light signal.

Confinement of a propagating light beam to the region of the fiber cores and power transfer from two closely placed fiber cores can be used to produce a series of fiber sensors based on evanescence (*Clark, 1988; Li, 1986; Murakami, 1981*). Figure 3.11 illustrates two fiber cores that have been placed in close proximity to one another. For single mode optical fiber (*Nolan, 1991*) this distance is approximately 10 to 20 microns.

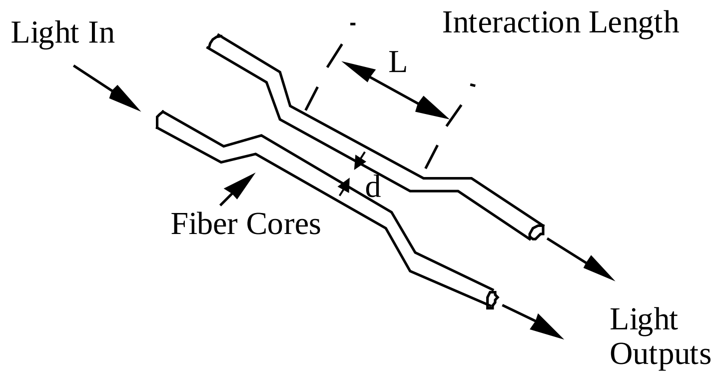


Figure 3.11: Evanescence based fiber optic sensors rely on the cross coupling of light between two closely spaced fiber optic cores. Variations in this distance due to temperature, pressure or strain offer environmental sensing capabilities.

When single mode fiber is used, there is considerable leakage of the propagating light beam mode beyond the core region into the cladding or medium around it. If a second fiber core is placed nearby this evanescent tail will tend to cross couple to the adjacent fiber core. The amount of cross coupling depends on a number of parameters including the wavelength of light, the relative index of refraction of the medium in which the fiber cores are placed, the distance between the cores and the interaction length. This type of fiber sensor can be used for the measurement of wavelength, spectral filtering, index of refraction and environmental effects acting on the medium surrounding the cores (temperature, pressure and strain). The difficulty with this sensor that is common to many fiber sensors is optimizing the design so that only the desired parameters are sensed.

Another way that light may be lost from an optical fiber is when the bend radius of the fiber exceeds the critical angle necessary to confine the light to the core area and there is leakage into the cladding. Microbending of the fiber locally can cause this to result with resultant intensity modulation of light propagating through an optical fiber. A series of microbend based fiber sensors have been built to sense vibration, pressure and other environmental effects (*Berthold, 1987; Miers, 1987; Spillman, 1980*). Figure 3.12 shows a typical layout of this type of device consisting of a light source, a section of optical fiber positioned in a microbend transducer designed to intensity modulate light in response to an environmental effect and a detector. In some cases, the microbend transducer can be implemented by using special fiber cabling or optical fiber that is simply optimized to be sensitive to microbending loss.

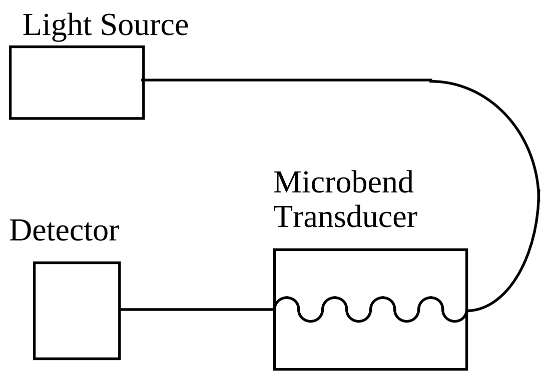


Figure 3.12: Microbend fiber sensors are configured so that an environmental effect results in an increase or decrease in loss through the transducer due to light loss resulting from small bends in the fiber.

One last example of an intensity based sensor is the grating based device (*Udd, 1985*) shown in Figure 3.13. Here an input optical light beam is collimated by a lens and passes through a dual grating system. One of the gratings is fixed while the other moves. With acceleration, the relative position of the gratings changes resulting in an intensity modulated signal on the output optical fiber.

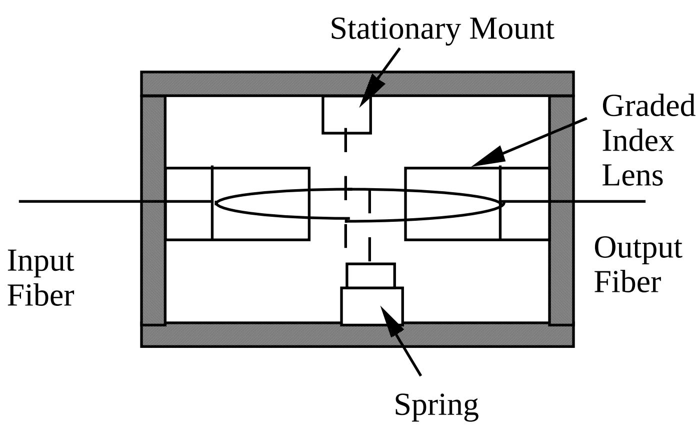


Figure 3.13: Grating based fiber intensity sensors measure vibration or acceleration via a highly sensitive shutter effect.

One of the limitations of this type of device is that as the gratings move from a totally transparent to a totally opaque position the relative sensitivity of the sensor changes as can be seen from Figure 3.14. For optimum sensitivity, the gratings should be in the half-open, half-closed position. Increasing sensitivity means finer and finer grating spacings, which in turn limit dynamic range.

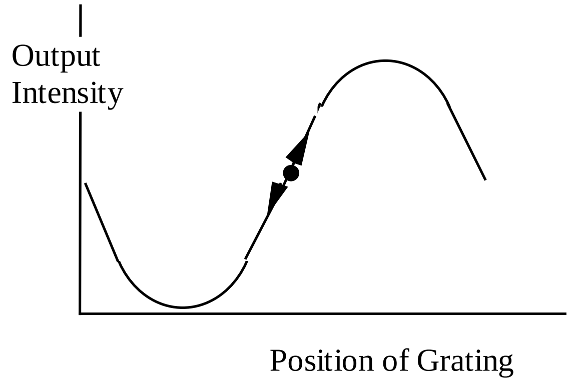


Figure 3.14: Dynamic range limitations of the grating based sensor of Figure 3.13 are due to smaller grating spacing increasing sensitivity at the expense of range.

To increase sensitivity without limiting dynamic range, use multiple part gratings that are offset by 90 degrees as shown in Figure 3.15. If two outputs are spaced in this manner, the resulting outputs are in quadrature as shown in Figure 3.16.

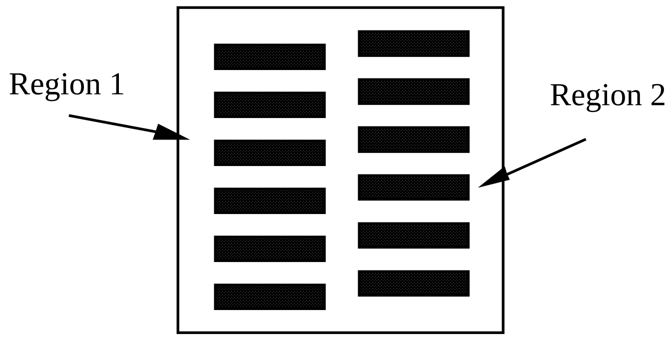


Figure 3.15: Dual grating mask with regions 90 degrees out of phase to support quadrature detection which allows grating based sensors to track through multiple lines.

When one output is at optimal sensitivity the other is at its lowest sensitivity and vice versa. By using both outputs for tracking, one can scan through multiple grating lines enhancing dynamic range and avoiding signal fade out associated with positions of minimal sensitivity.

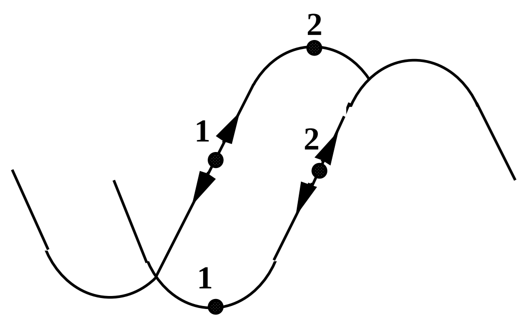


Figure 3.16: Diagram illustrating quadrature detection method that allows one area of maximum sensitivity while the other reaches a minimum and vice versa, allowing uniform sensitivity over a wide dynamic range.

Intensity based fiber optic sensors have a series of limitations imposed by variable losses in the system that are not related to the environmental effect to be measured. Potential error sources include variable losses due to connectors and splices, microbending loss, macrobending loss, and mechanical creep and misalignment of light sources and detectors. To circumvent these problems many of the successful higher performance intensity based fiber sensors employ dual wavelengths. One of the wavelengths is used to calibrate out all of the errors due to undesired intensity variations by bypassing the sensing region. An alternative approach is to use fiber optic sensors that are inherently resistant to errors induced by intensity variations. In the next section a series of spectrally based fiber sensors that have this characteristic are discussed.

3.2 SPECTRALLY BASED FIBER OPTIC SENSORS

Spectrally based fiber optic sensors depend on a light beam being modulated in wavelength by an environmental effect. Examples of these types of fiber sensors include those based on blackbody radiation, absorption, fluorescence, etalons and dispersive gratings.

One of the simplest of these types of sensors is the blackbody sensor of Figure 3.17. A blackbody cavity is placed at the end of an optical fiber. When the cavity rises in temperature, it starts to glow and act as a light source.

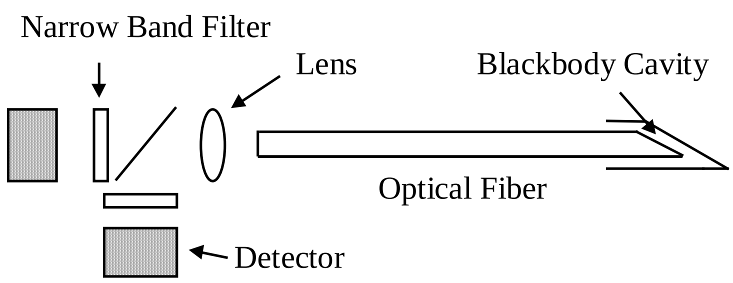


Figure 3.17: Blackbody fiber optic sensors allow the measurement of temperature at a hot spot and are most effective at temperatures of higher than 300 degrees C.

Detectors in combination with narrow band filters are then used to determine the profile of the blackbody curve and in turn the temperature as in Figure 3.18. This type of sensor has been successfully commercialized and has been used to measure temperature to within a few degrees C under intense RF fields. The performance and accuracy of this sensor is better at higher temperatures and falls off at temperatures on the order of 200 degrees C because of low signal to noise ratios. Care must be taken to insure that the hottest spot is the blackbody cavity and not on the optical fiber lead itself as this can corrupt the integrity of the signal.

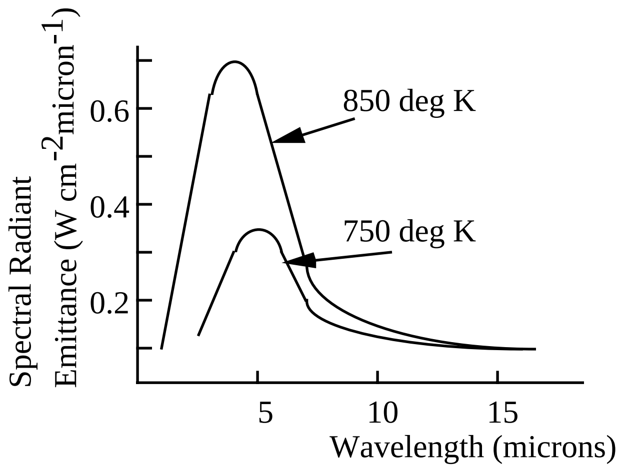


Figure 3.18: Blackbody radiation curves provide unique signatures for each temperature.

Another type of spectrally based temperature sensor is shown in Figure 3.19 and is based on absorption (*Christensen, 1987*). In this case, a Gallium Arsenide (GaAs) sensor probe is used in combination with a broadband light source and input/output optical fibers. The absorption profile of the probe is temperature dependent and may be used to determine temperature.

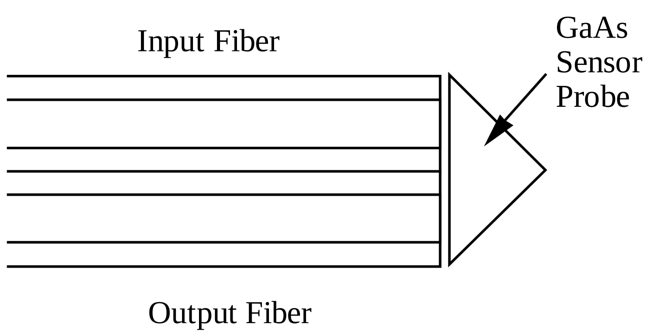


Figure 3.19: Fiber optic sensor based on variable absorption of materials such as GaAs allows the measurement of temperature and pressure.

Fluorescent based fiber sensors (*Gratten, 1986; Schwab, 1989*) that are being widely used for medical and chemical sensing applications, can also be used for physical parameter measurements such as temperature, viscosity and humidity. There are a number of configurations for these sensors and Figure 3.20 illustrates two of the most common ones. In the case of the end tip sensor, light propagates down the fiber to a probe of fluorescent material. The resultant fluorescent signal is captured by the same fiber and directed back to an output demodulator. The light sources can be pulsed and probes have been made that depend on the time rate of decay of the light pulse.

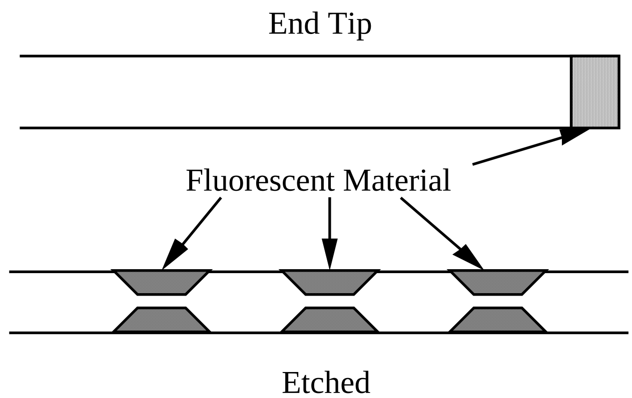


Figure 3.20: Fluorescent fiber optic sensor probe configurations can be used to support the measurement of physical parameters as well as the presence or absence of chemical species. These probes may be configured to be single ended or multipoint by using side etch techniques and attaching the fluorescent material to the fiber.

In the continuous mode, parameters such as viscosity, water vapor content and degree of cure in carbon fiber reinforced epoxy and thermoplastic composite materials can be monitored.

An alternative is to use the evanescent properties of the fiber, etch regions of the cladding away, and refill them with fluorescent material. By sending a light pulse down the fiber and looking at the resulting fluorescence, a series of sensing regions may be time division multiplexed.

It is also possible to introduce fluorescent dopants into the optical fiber itself. This approach would cause the entire optically activated fiber to fluoresce. By using time division multiplexing, various regions of the fiber could be used to make a distributed measurement along the fiber length.

In many cases, users of fiber sensors would like to have the fiber optic analog of conventional electronic sensors. An example is the electrical strain gauge that is used widely by structural engineers. Fiber grating sensors (*Ball, 1993; Dunphy, 1990; Morey, 1990*) can be configured to have gauge lengths from 1 mm to approximately 1 cm, with sensitivity comparable to conventional strain gauges.

This sensor is fabricated by "writing" a fiber grating onto the core of a Germanium doped optical fiber. This can be done in a number of ways. One method, which is illustrated by Figure 3.21, uses two short wavelength laser beams that are angled to form an interference pattern through the side of the optical fiber. The interference pattern consists of bright and dark bands that represent local changes in the index of refraction in the core region of the fiber. Exposure time for making these gratings varies from minutes to hours, depending on the dopant concentration in the fiber, the wavelengths used, the optical power level and the imaging optics.

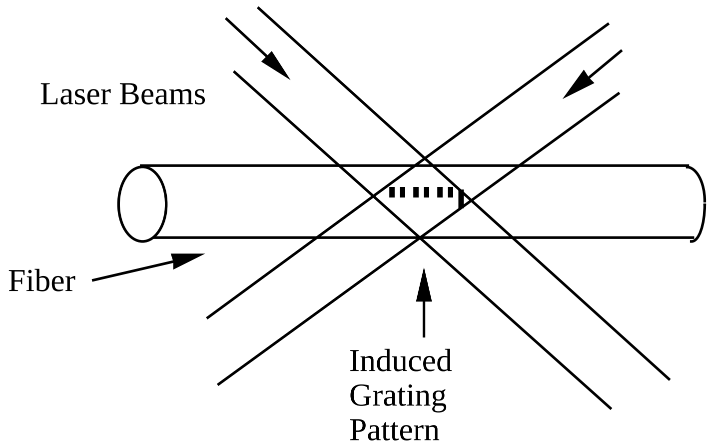


Figure 3.21: Fabrication of a fiber grating sensor can be accomplished by imaging to short wavelength laser beams through the side of the optical fiber to form an interference pattern. The bright and dark fringes that are imaged on the core of the optical fiber induce an index of refraction variation resulting in a grating along the fiber core.

Other methods that have been used include the use of phase masks, and interference patterns induced by short high-energy laser pulses. The short duration pulses have the potential to be used to write fiber gratings into the fiber as it is being drawn.

Substantial efforts are being made by laboratories around the world to improve the manufacturability of fiber gratings as they have the potential to be used to support optical communication as well as sensing technology.

Once the fiber grating has been fabricated, the next major issue is how to extract information. When used as a strain sensor the fiber grating is typically attached to, or embedded in, a structure. As the fiber grating is expanded or compressed, the grating period expands or contracts, changing the gratings spectral response.

For a grating operating at 1300 nm, the change in wavelength is about 10^{-3} nm per microstrain. This type of resolution requires the use of spectral demodulation techniques that are much better than those associated with conventional spectrometers. Several demodulation methods have been suggested using fiber gratings, etalons and interferometers (*Jackson, 1993; Kersey, 1992*). Figure 3.22 illustrates a system that uses a reference fiber grating. The action of the reference fiber grating is to act as a modulator filter. By using similar gratings for the reference and signal gratings and adjusting the reference grating to line up with the active grating, an accurate closed loop demodulation system may be implemented.

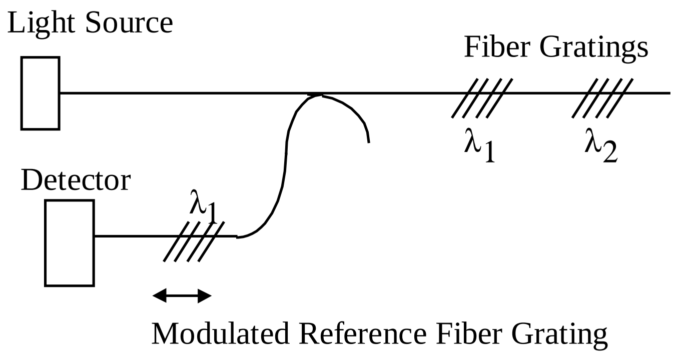


Figure 3.22: Fiber grating demodulation systems require very high-resolution spectral measurements. One way to accomplish this is to beat the spectrum of light reflected by the fiber grating against the light transmission characteristics of a reference grating.

An alternative demodulation system for gratings uses fiber etalons such as those shown in Figure 3.23. The spacing and reflectivity of the fiber ends determines the spectral filtering action. The performance is frequently characterized by "finesse", F, which is a function of the reflectivity. The results are illustrated by Figure 3.24.

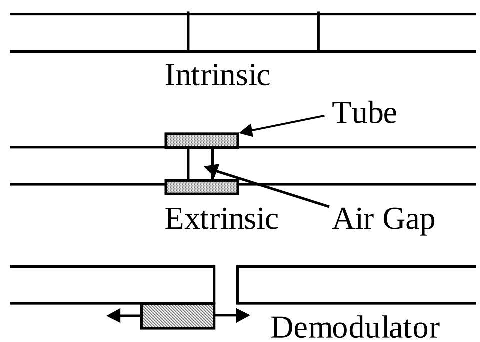


Figure 3.23: Intrinsic fiber etalons are formed by in line reflective mirrors that can be embedded into the optical fiber. Extrinsic fiber etalons are formed by two mirrored fiber ends in a capillary tube. A fiber etalon based spectral filter or demodulator is formed by two reflective fiber ends that have a variable spacing.

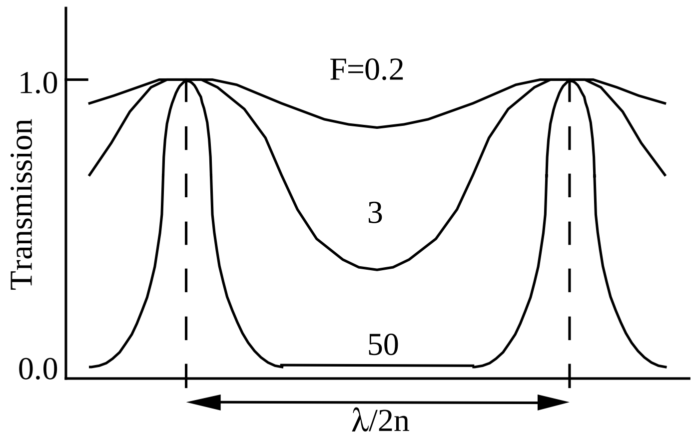


Figure 3.24: Diagram illustrating the transmission characteristics of a fiber etalon as a function of finesse, which increases with mirror reflectivity.

The fiber etalons in Figure 3.23 can also be used as sensors (*Lee, 1988; Lee, 1990; Saaski, 1986*) for measuring strain as the distance between mirrors in the fiber determines their transmission characteristics. The mirrors can be fabricated directly into the fiber by cleaving the fiber, coating the end with titanium dioxide, and then resplicing. The second approach is to cleave the fiber ends and insert them into a capillary tube with an air gap. These approaches are being investigated for applications where multiple, in-line strain sensors are required.

For many applications a single point sensor is adequate. In this case the etalon can be fabricated independently and attached to the end of the fiber. Figure 3.25 shows a series of etalons that have been configured to measure pressure, temperature and refractive index of liquids.

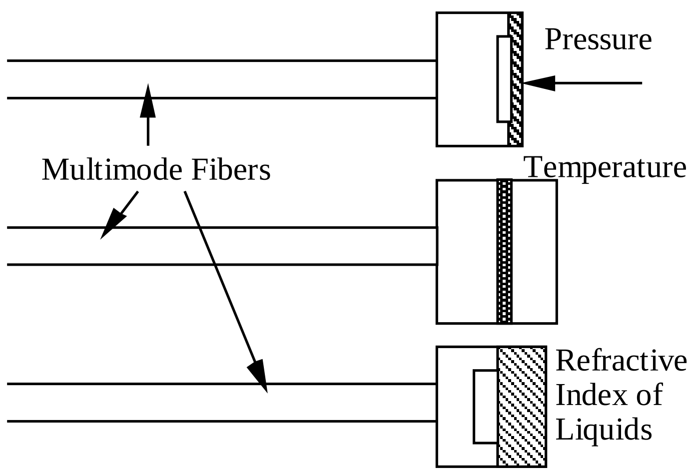


Figure 3.25: Hybrid etalon based fiber optic sensors often consist of micromachined cavities that are placed on the end of optical fibers and can be configured so that sensitivity to one environmental effect is optimized.

The pressure sensor has a diaphragm has been designed to deflect and change the size of the air gap, thus changing the spectral characteristics of the reflected light. Pressures from 15 to 2000 psi can be measured by changing the diaphragm thickness. Accuracy is about 0.1 percent of full scale (*Saaski*).

The etalon temperature sensor can be formed by directly in the fiber by splicing in mirrors. Temperatures from 70 to 500 degree K can be measured and a 100 degree K range could have a resolution as good as 0.1 degree K (*Saaski*).

Refractive index of liquids can be determined by forming holes in the etalon so that the liquid can flow through the etalon, thus changing the index of refraction in the space between the fiber and the reflecting surface. These devices have been commercialized and are sold with instrument packages (*Saaski*).

3.3 INTERFEROMETRIC FIBER OPTIC SENSORS

One of the areas of greatest interest has been in the development of high performance interferometric fiber optic sensors. Substantial efforts have been undertaken on Sagnac interferometers, ring resonators, Mach-Zehnder and Michelson interferometers as well as dual mode, polarimetric, grating and etalon based interferometers. In this section, the Sagnac, Mach-Zehnder, and Michelson interferometers are briefly reviewed.

3.3.1 The Sagnac Interferometer

The Sagnac interferometer has been principally used to measure rotation (*Burns, 1994; Ezekial, 1991; Lefevre, 1993; Smith, 1989*) and is a replacement for ring laser gyros and mechanical gyros. It may also be employed to measure time varying effects such as acoustics, vibration and slowly varying phenomenon such as strain. By using multiple interferometer configurations, it is possible to employ the Sagnac interferometer as a distributed sensor capable of measuring the amplitude and location of a disturbance.

The single most important application of fiber optic sensors in terms of commercial value is the fiber optic gyro. It was recognized very early that the fiber optic gyro offered the prospect of an all solid-state inertial sensor with no moving parts, unprecedented reliability, and the prospect of having a very low cost.

The potential of the fiber optic gyro is being realized as several manufacturers worldwide are producing them in large quantities to support automobile navigation systems, pointing and tracking of satellite antennas, inertial measurement systems for commuter aircraft and missiles, and as the backup guidance system for the Boeing 777. They are also being baselined for such future programs as the Comanche helicopter and are being developed to support long duration space flights.

Other applications where fiber optic gyros are being used include mining operations, tunneling, attitude control for a radio controlled helicopter, cleaning robots, antenna pointing and tracking, and guidance for unmanned trucks and carriers.

Two types of fiber optic gyros are being developed. The first type is an open loop fiber optic gyro with a dynamic range on the order of 1000 to 5000, with scale factor accuracy of about 0.5 percent and sensitivities that vary from less than 0.01 deg/hr to 100 deg/hr and higher (*Ezekial, 1991*). The dynamic range is the range from the threshold rotation rate to the highest measurable rotation rate; thus, a threshold rate of .1° per second and a dynamic range of 1000 would have a maximum rotation rate of 100° per second. The accuracy number includes non-linearity and hysterisis effects. These fiber gyros are generally used for low cost applications where dynamic range and linearity are not the crucial issues.

The second type is the closed loop fiber optic gyro that may have a dynamic range of 10^6 and scale factor linearity of 10 ppm or better (*Ezekial, 1991*). These types of fiber optic gyros are primarily targeted at medium to high accuracy navigation applications that have high turning rates and require high linearity and large dynamic ranges.

The basic open loop fiber optic gyro is illustrated by Figure 3.26. A broadband light source such as a light emitting diode is used to couple light into an input/output fiber coupler. The input light beam passes through a polarizer that is used to insure the reciprocity of the counterpropagating light beams through the fiber coil. The second central coupler splits the two light beams into the fiber optic coil where they pass through a modulator that is used to generate a time varying output signal indicative of rotation. The modulator is offset from the center of the coil to impress a relative phase difference between the counterpropagating light beams. After passing through the fiber coil the two light beams recombine and pass back though the polarizer and are directed onto the output detector.

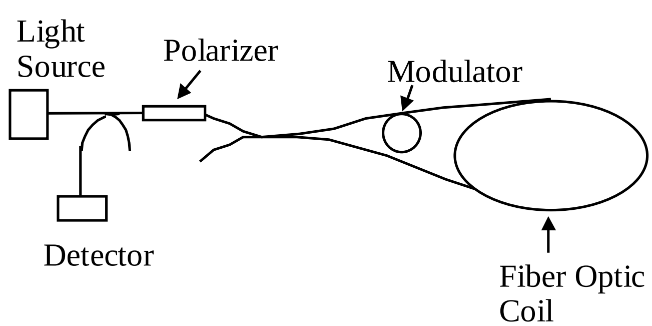


Figure 3.26: Open loop fiber optic gyro is the simplest and lowest cost rotation sensor. They are widely used in commercial applications where their dynamic range and linearity limitations are not constraining.

When the fiber gyro is rotated in a clockwise direction the entire coil is displaced slightly, increasing the time it takes light to traverse the fiber optic coil. The speed of light is invariant with respect to the frame of reference; so coil rotation increases path length when viewed from outside the fiber. Thus the clockwise propagating light beam has to go through a slightly longer optical pathlength than the counterclockwise beam which is moving in a direction opposite to the motion of the fiber coil. The net phase difference between the two beams is proportional to the rotation rate.

By including a phase modulator loop offset from the fiber coil a time difference in the arrival of the two light beams is introduced, and an optimized demodulation signal can be realized. This is shown on the right side in Figure 3.27. In the absence of the loop the two light beams traverse the same optical path, are in phase with each other, and are shown on the left-hand curve of Figure 3.27.

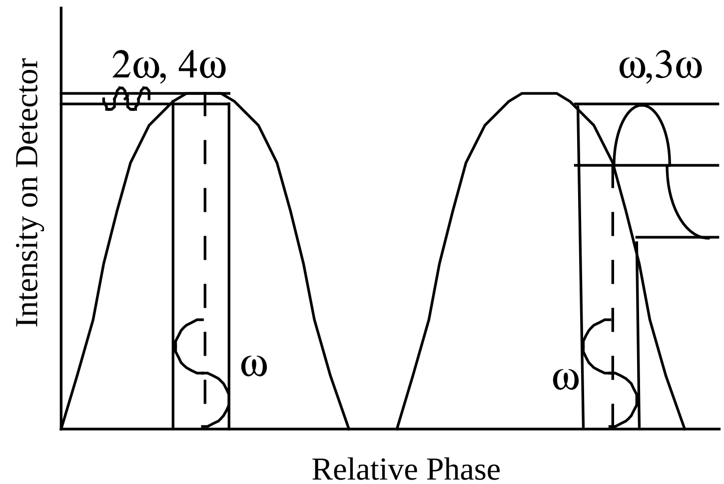


Figure 3.27: An open loop fiber optic gyro has predominantly even order harmonics in the absence of rotation. Upon rotation, the open loop fiber optic gyro has odd harmonic output whose amplitude indicates the magnitude of the rotation rate and phase indicates direction.

The result is that the first or a higher order odd harmonic can be used as a rotation rate output and improved dynamic range and linearity is realized.

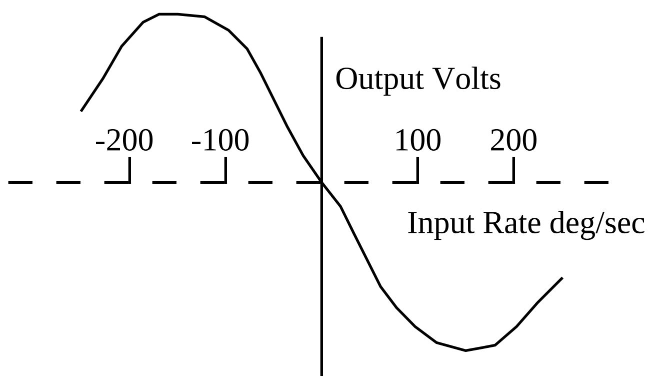


Figure 3.28: A typical open loop fiber optic gyro output obtained by measuring one of the odd harmonic output components amplitude and phase, results in a sinusoidal output that has a region of good linearity centered about the zero rotation point.

Further improvements in dynamic range and linearity can be realized by using a "closed loop" configuration where the phase shift induced by rotation is compensated by an equal and opposite artificially imposed phase shift. One way to accomplish this is to introduce a frequency shifter into the loop as is shown in Figure 3.29.

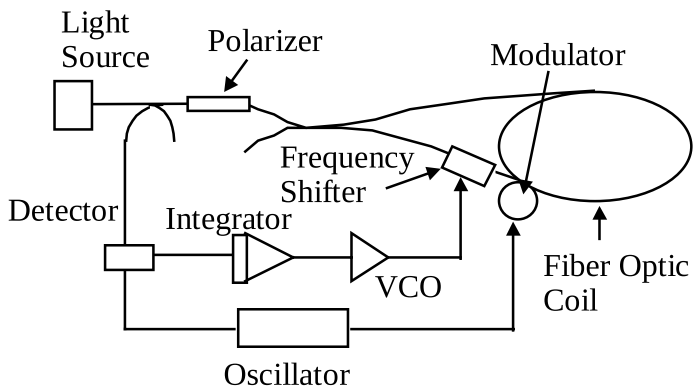


Figure 3.29: Closed loop fiber optic gyros use an artificially induced nonreciprocal phase between counterpropagating light beams to counterbalance rotationally induced phase shifts. These fiber gyros have the wide dynamic range and high linearity needed to support stringent navigation requirements.

The relative frequency difference of the light beams propagating in the fiber loop can be controlled resulting in a net phase difference that is proportional to the length of the fiber coil and the frequency shift. In Figure 3.29, using a modulator in the fiber optic coil generates a phase shift at a rate ω. When the coil is rotated, a first harmonic signal is induced with phase that depends on rotation rate in a manner similar to that described above with respect to open loop fiber gyros. By using rotationally induced first harmonic as an error signal, the frequency shift can be adjusted by using a synchronous demodulator behind the detector to integrate the first harmonic signal into a corresponding voltage. This voltage is applied to a voltage-controlled oscillator whose output frequency is applied to the frequency shifter in the loop so that the phase relationship between the counterpropagating light beams is locked to a single value.

It is possible to use the Sagnac interferometer for other sensing and measurement tasks. Examples include: slowly varying measurements of strain with 100 micron resolution over distances of about 1 km (*Michal, 1986*), spectroscopic measurements of wavelength to about 2 nm (*Udd, 1990*) and optical fiber characterization such as thermal expansion to accuracies of about 10 ppm (*Udd, 1990*). In each of these applications, frequency shifters are used in the Sagnac loop to obtain controllable frequency offsets between the counterpropagating light beams.

Another class of fiber optic sensors, based on the Sagnac interferometer, can be used to measure rapidly varying environmental signals such as sound (*Dakin, 1987; Udd, 1991c*). Figure 3.30 illustrates two interconnected Sagnac loops (*Udd, 1991c)* that can be used as a distributed acoustic sensor. The WDM (wavelength division multiplexer) in the figure is a device which either couples two wavelengths together, λ_1 and λ_2 in this case, or separates them.

The sensitivity of this Sagnac acoustic sensor depends on the location of the signal. If the signal is in the center of the loop the amplification is zero, as both counterpropagating light beams arrive at the center of the loop at the same time. As the signal moves away from the center, the output increases. When two Sagnac loops are superposed as in Figure 3.30, the two outputs may be summed to give an indication of the amplitude of the signal and ratioed to determine position.

Several other combinations of interferometers have been tried for position and amplitude determinations and the first reported success consisted of a combination of the Mach-Zehnder and Sagnac interferometer (*Dakin, 1987*).

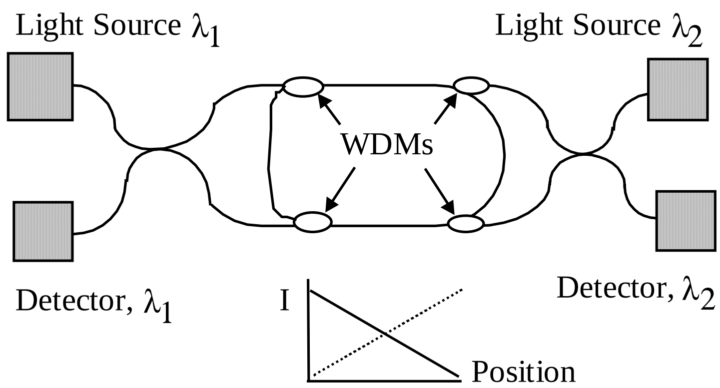


Figure 3.30: Distributed fiber optic acoustic sensor based on interlaced Sagnac loops allows the detection of the location and the measurement of the amplitude along a length of optical fiber that may be many kilometers long.

3.3.2 The Mach-Zehnder and Michelson Interferometers

One of the great advantages of all fiber interferometers, such as Mach-Zehnder and Michelson interferometers (*Dandridge, 1991*) in particular, is that they have extremely flexible geometry's and high sensitivity that allow the possibility of a wide variety of high performance elements and arrays as shown in Figure 3.31.

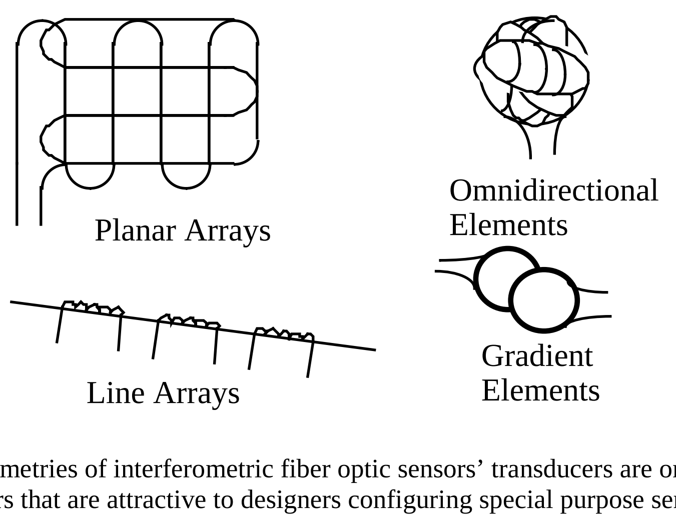


Figure 3.31: Flexible geometries of interferometric fiber optic sensors’ transducers are one of the features of fiber sensors that are attractive to designers configuring special purpose sensors.

Figure 3.32 shows the basic elements of a Mach-Zehnder interferometer, which are a light source/coupler module, a transducer and a homodyne demodulator. The light source module usually consists of a long coherence length isolated laser diode, a beam splitter to produce two light beams and a means of coupling the beams to the two legs of the transducer. The transducer is configured to sense an environmental effect by isolating one light beam from the environmental effect and using the action of the environmental effect on the transducer is to induce an optical path length difference between the two light beams. Typically homodyne demodulators, as well as various heterodyne schemes, are used to detect the difference in optical path length (*Dandridge, 1991*).

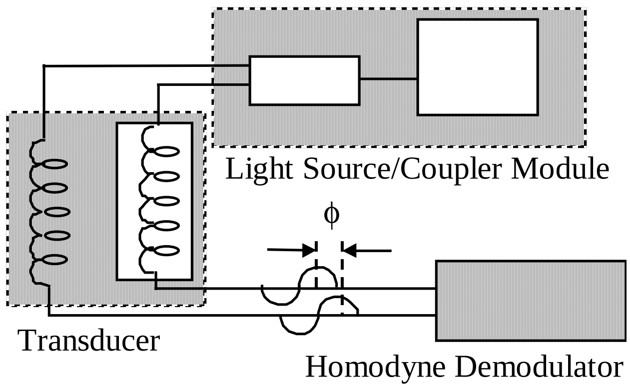


Figure 3.32: The basic elements of the fiber optic Mach-Zehnder interferometer are a light source module to split a light beam into two paths, a transducer used to cause an environmentally dependent differential optical path length between the two light beams, and a demodulator that measures the resulting path length difference between the two light beams.

One of the basic issues with the Mach-Zehnder interferometer is that the sensitivity will vary as a function of the relative phase of the light beams in the two legs of the interferometer, as shown in Figure 3.33. One way to solve the signal fading problem is to introduce a piezoelectric fiber stretcher into one of the legs and adjust the relative path length of the two legs for optimum sensitivity. Another approach has the same quadrature solution as the grating based fiber sensors discussed earlier.

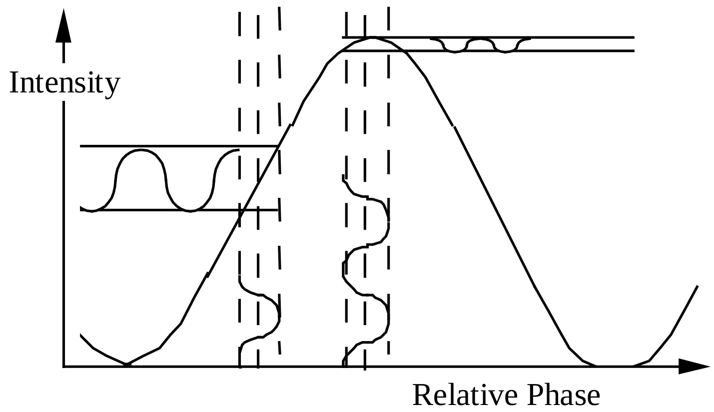


Figure 3.33: In the absence of compensating demodulation methods, the sensitivity of the Mach-Zehnder varies with the relative phase between the two light beams. It falls to low levels when the light beams are completely in or out of phase.

Figure 3.34 illustrates a homodyne demodulator. The demodulator consists of two parallel optical fibers that feed the light beams from the transducer into a graded index (GRIN) lens. The output from the graded index lens is an interference pattern that “rolls” with the relative phase of the two input light beams. If a split detector is used with a photomask arranged so that the opaque and transparent line pairs on the mask in front of the split detector match the interference pattern periodicity and are 90 degrees out of phase on the detector faces, sine and cosine outputs result.

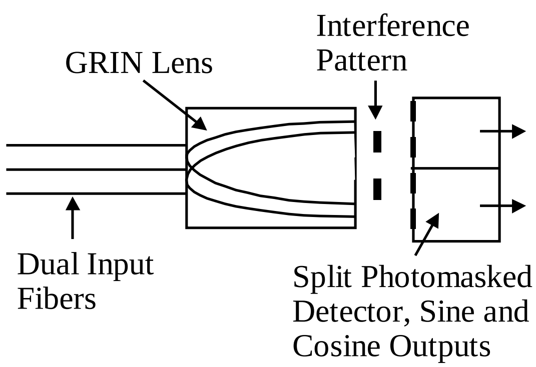


Figure 3.34: Quadrature demodulation avoids signal fading problems. The method shown here expands the two beams into an interference pattern that is imaged onto a split detector.

These outputs may be processed using quadrature demodulation electronics as shown in Figure 3.35. The result is a direct measure of the phase difference.

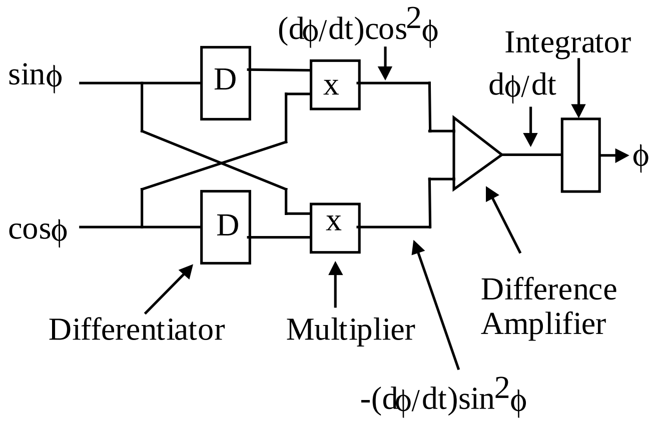


Figure 3.35: Quadrature demodulation electronics take the sinusoidal outputs from the split detector and convert them via cross multiplication and differentiation into an output that can be integrated to form the direct phase difference.

Further improvements on these techniques have been made; notably the phase generated carrier approach shown in Figure 3.36. A laser diode is current modulated resulting in the output frequency of the laser diode being frequency modulated as well. If a Mach-Zehnder interferometer is arranged so that its reference and signal leg differ in length by an amount (L_1-L_2) then the net phase difference between the two light beams is:

$$\frac{2\pi F(L_1 - L_2)n}{c} \tag{3-1}$$

where n is the index of refraction of the optical fiber and c is the speed of light in vacuum. If the current modulation is at a rate ω then relative phase differences are modulated at this rate and the output on the detector will be odd and even harmonics of it. The signals riding on the carrier harmonics of ω and 2ω are in quadrature with respect to each other and can be processed using electronics similar to those of Figure 3.35.

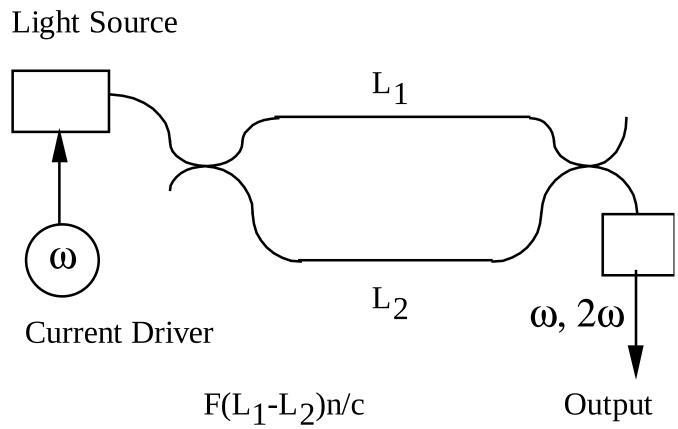


Figure 3.36: The phase generated carrier technique allows quadrature detection via monitoring even and odd harmonics induced by a sinusoidally frequency modulated light source used in combination with a length offset Mach-Zehnder interferometer to generate a modulated phase output whose first and second harmonics correspond to sine and cosine outputs.

The Michelson interferometer shown in Figure 3.37 is in many respects similar to the Mach-Zehnder. The major difference is that mirrors have been put on the ends of the interferometer legs. This results in very high levels of back reflection into the light source greatly degrading the performance of early systems. By using improved diode pumped YAG (Yttrium Aluminum Garnet) ring lasers as light sources these problems have been largely overcome. In combination with the recent introduction of phase conjugate mirrors to eliminate polarization fading, the Michelson is becoming an alternative for systems that can tolerate the relatively high present cost of these components.

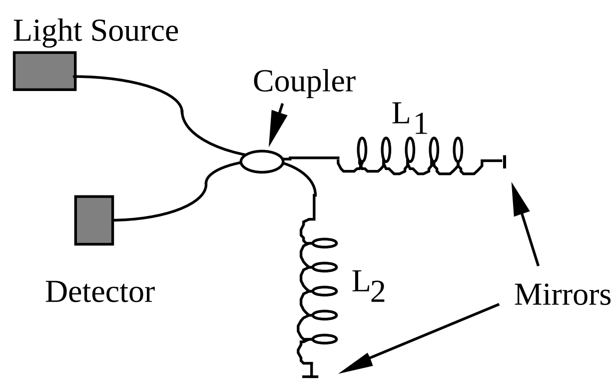


Figure 3.37: The fiber optic Michelson interferometer consists of two mirrored fiber ends and can utilize many of the demodulation methods and techniques associated with the Mach-Zehnder.

In order to implement an effective Mach-Zehnder or Michelson based fiber sensor it is necessary to construct an appropriate transducer. This can involve a fiber coating that could be optimized for acoustic, electric or magnetic field response. In Figure 3.38 a two-part coating is illustrated that consists of a primary and secondary layer. These layers are designed for optimal response to pressure waves and for minimal acoustic mismatches between the medium in which the pressure waves propagate and the optical fiber.

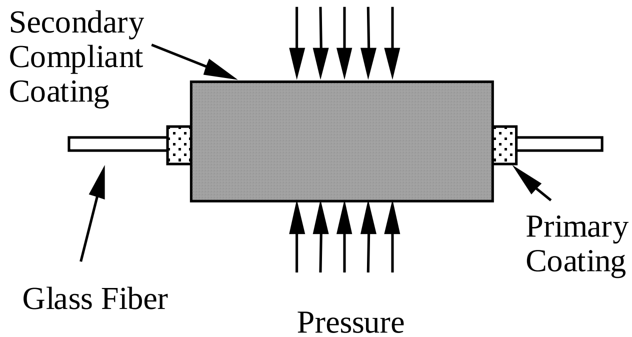


Figure 3.38: Coatings can be used to optimize the sensitivity of fiber sensors. An example would be to use soft and hard coatings over an optical fiber to minimize the acoustic mismatch between acoustic pressure waves in water and the glass optical fiber.

These coated fibers are often used in combination with compliant mandrills or strips of material as in Figure 3.39 that act to amplify the environmentally induced optical path length difference.

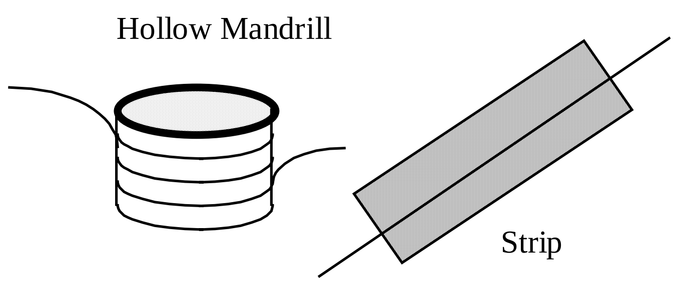


Figure 3.39: Optical fiber bonded to hollow mandrills and strips of environmentally sensitive material are common methods used to mechanically amplify environmental signals for detection by fiber sensors.

In many cases the mechanical details of the transducer design are critical to good performance such as the seismic/vibration sensor of Figure 3.40. Generally, the Mach-Zehnder and Michelson interferometers can be configured with sensitivities that are better than 10^{-6} radians per square root Hertz. For optical receivers, the noise level decreases as a function of frequency. This phenomenon results in specifications in radians per square root Hertz. As an example, a sensitivity of 10^{-6} radians per square root Hertz at 1 Hertz means a sensitivity of 10^{-6} radians while at 100 Hertz, the sensitivity is 10^{-7} radians. As an example, a sensitivity of 10^{-6} radian per square root Hertz means that for a 1 meter long transducer, less than 1/6 micron of length change can be resolved at 1 Hertz bandwidths (*Bucholtz*, *1989*). The best performance for these sensors is usually achieved at higher frequencies because of problems associated with the sensors also picking up environmental signals due to temperature fluctuations, vibrations and acoustics that limit useful low frequency sensitivity.

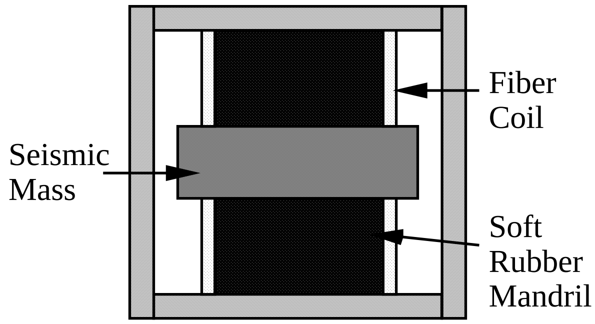


Figure 3.40: Differential methods are used to amplify environmental signals. In this case, a seismic/vibration sensor consists of a mass placed between two fiber coils and encased in a fixed housing.

3.4 MULTIPLEXING AND DISTRIBUTED SENSING

Many of the intrinsic and extrinsic sensors may be multiplexed (*Kersey*, *1991*) offering the possibility of large numbers of sensors being supported by a single fiber optic line. The techniques that are most commonly employed are time, frequency, wavelength, coherence, polarization and spatial multiplexing.

Time division multiplexing employs a pulsed light source launching light into an optical fiber and analyzing the time delay to discriminate between sensors. This technique is commonly employed to support distributed sensors where measurements of strain, temperature or other parameters are collected. Figure 3.41 illustrates a time division multiplexed system that uses microbend sensitive areas on pipe joints.

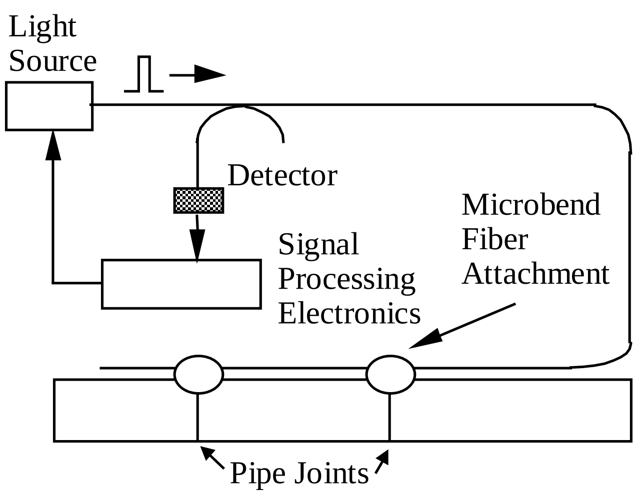


Figure 3.41: Time division multiplexing methods can be used in combination with microbend sensitive optical fiber to locate the position of stress along a pipeline.

As the pipe joints are stressed microbending loss increases and the time delay associated with these losses allows the location of faulty joints.

The entire length of the fiber can be made microbend sensitive and Rayleigh scattering loss are used to support a distributed sensor that will predominantly measure strain. Other types of scattering from optical pulses propagating down optical fiber have been used to support distributed sensing, notably Raman scattering for temperature sensors has been made into a commercial product by York Technology and Hitachi. These units can resolve temperature changes of about 1 degree C with spatial resolution of 1 meter for a 1 km sensor using an integration time of about 5 minutes. Brillioun scattering has been used in laboratory experiments to support both strain and temperature measurements.

A frequency division multiplexed system is shown in Figure 3.42. In this example a laser diode is frequency chirped by driving it with a sawtooth current drive. Successive Mach-Zehnder interferometers are offset with incremental lengths ($L-L_1$), ($L-L_2$), and ($L-L_3$) which differ sufficiently that the resultant carrier frequency of each sensor $(dF/dt)(L-L_n)$ is easily separable from the other sensors via electronic filtering of the output of the detector.

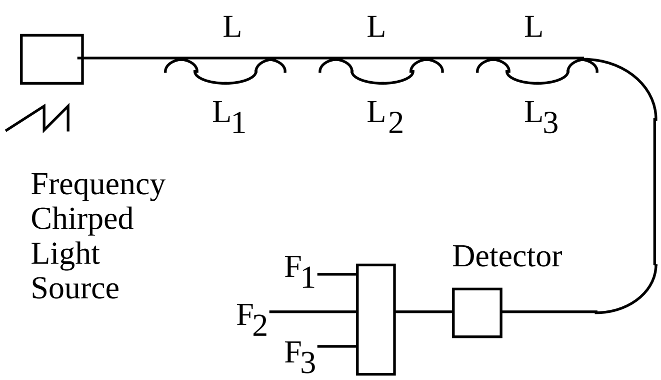


Figure 3.42: Frequency division multiplexing can be used to tag a series of fiber sensors, as in this case the Mach-Zehnder interferometers are shown with a carrier frequency on which the output signal ride.

Wavelength division multiplexing is one of the best methods of multiplexing as it uses optical power very efficiently. It also has the advantage of being easily integrated into other multiplexing systems allowing the possibility of large numbers of sensors being supported in a single fiber line. Figure 3.43 illustrates a system where a broadband light source, such as a light emitting diode, is coupled into a series of fiber sensors that reflect signals over wavelength bands that are subsets of the light source spectrum. A dispersive element, such as a grating or prism, is used to separate out the signals from the sensors onto separate detectors.

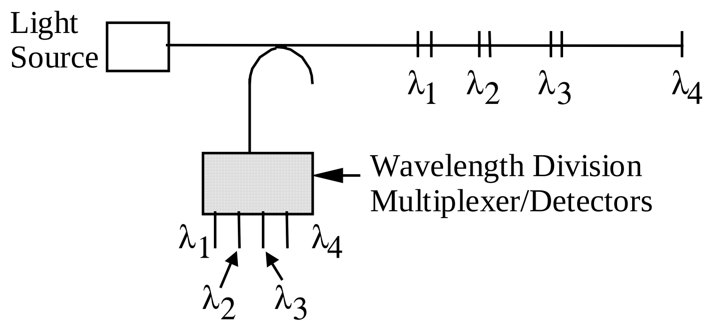


Figure 3.43: Wavelength division multiplexing are often very energy efficient. A series of fiber sensors are multiplexed by being arranged to reflect in a particular spectral band that is split via a dispersive element onto separate detectors.

Light sources can have widely varying coherence lengths depending on their spectrum. By using light sources that have coherence lengths that are short compared to offsets between the reference and signal legs in Mach-Zehnder interferometers and between successive sensors, a coherence multiplexed system similar to Figure 3.44 may be set up. The signal is extracted by putting a rebalancing interferometer in front of each detector so that the sensor signals may be processed. Coherence multiplexing is not as commonly used as time, frequency and wavelength division multiplexing because of optical power budgets and the additional complexities in setting up the optics properly. It is still a potentially powerful technique and may become more widely used as optical component performance and availability continue to improve, especially in the area of integrated optic chips where control of optical pathlength differences is relatively straightforward.

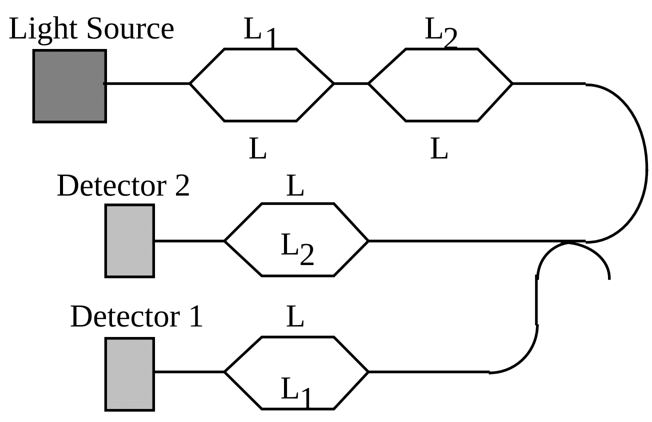


Figure 3.44: A low coherence light source is used to multiplex two Mach-Zehnder interferometers by using offset lengths and counterbalancing interferometers.

One of the least commonly used techniques is polarization multiplexing. In this case, the idea is to launch light with particular polarization states and extract each state. A possible application is shown in Figure 3.45 where light is launched with two orthogonal polarization modes;

preserving fiber and evanescent sensors have been set up along each of the axes. A polarizing beamsplitter is used to separate out the two signals. There is a recent interest in using polarization preserving fiber in combination with time domain techniques to form polarization based distributed fiber sensors. This has potential to offer multiple sensing parameters along a single fiber line.

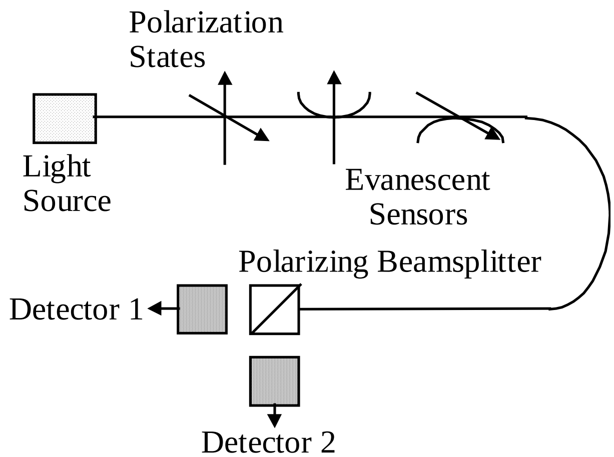


Figure 3.45: Polarization multiplexing is used to support two fiber sensors that access the cross polarization states of polarization preserving optical fiber.

Finally, it is possible to use spatial techniques to generate large sensor arrays using relatively few input and output optical fibers. Figure 3.46 shows a 2 by 2 array of sensors where two light sources are amplitude modulated at different frequencies. Two sensors are driven at one frequency and two more at the second. The signals from the sensors are put onto two output fibers each carrying a sensor signal from two sensors at different frequencies.

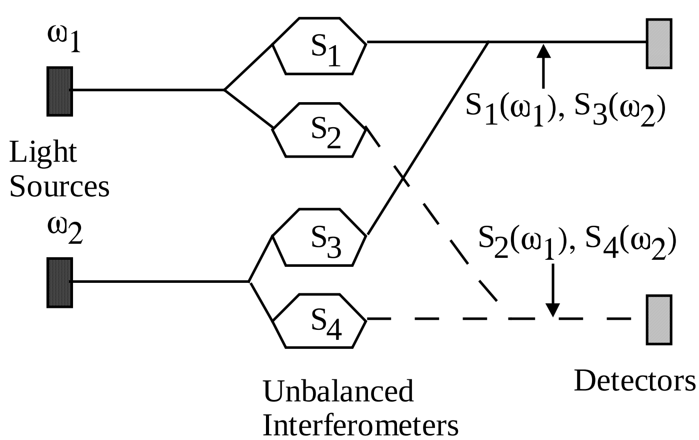


Figure 3.46: Spatial multiplexing of four fiber optic sensors may be accomplished by operating two light sources with different carrier frequencies and cross coupling the sensor outputs onto two output fibers.

This sort of multiplexing is easily extended to ‘m’ input fibers and ‘n’ output fibers to form ‘m’ by ‘n’ arrays of sensors as in Figure 3.47.

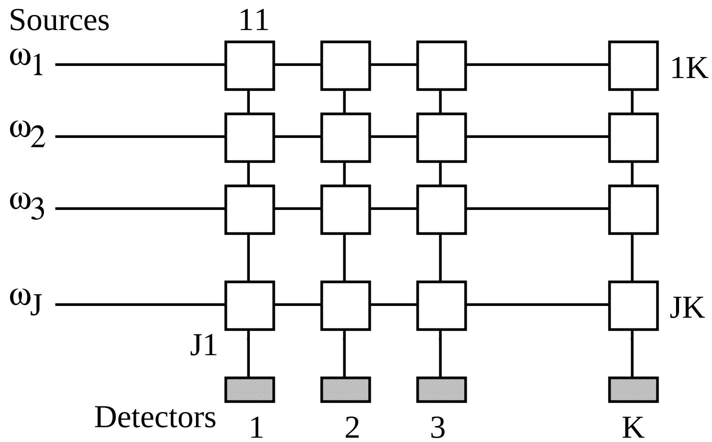


Figure 3.47: Extensions of spatial multiplexing the JK sensors can be accomplished by operating J light sources at J different frequencies and cross coupling to K output fibers.

All of these multiplexing techniques can be used in combination with one another to form extremely large arrays.

3.5 APPLICATIONS

Fiber optic sensors are being developed and used in two major ways. The first is as a direct replacement for existing sensors where the fiber sensor offers significantly improved performance, reliability, safety and/or cost advantages to the end user. The second area is the development and deployment of fiber optic sensors in new market areas.

For the case of direct replacement, the inherent value of the fiber sensor, to the customer, has to be sufficiently high to displace older technology. Because this often involves replacing technology the customer is familiar with, the improvements must be substantial.

The most obvious example of a fiber optic sensor succeeding in this arena is the fiber optic gyro, which is displacing both mechanical and ring laser gyros for medium accuracy devices. As this technology matures it can be expected that the fiber gyro will dominate large segments of this market.

Significant development efforts are underway in the United States in the area of fly-by-light (*Udd, 1994*) where conventional electronic sensor technology are targeted to be replaced by equivalent fiber optic sensor technology that offers sensors with relative immunity to electromagnetic interference, significant weight savings and safety improvements.

In manufacturing, fiber sensors are being developed to support process control. Oftentimes the selling points for these sensors are improvements in environmental ruggedness and safety, especially in areas where electrical discharges could be hazardous.

One other area where fiber optic sensors are being mass-produced is the field of medicine, (*Katzir, 1993; Lieberman, 1993; Milanovich, 1993; Wolfbeis, 1993*) where they are being used to measure blood gas parameters and dosage levels. Because these sensors are completely passive they pose no electrical shock threat to the patient and their inherent safety has lead to a relatively rapid introduction.

The automotive industry, construction industry and other traditional users of sensors remain relatively untouched by fiber sensors, mainly because of cost considerations. This can be expected to change as the improvements in optoelectronics and fiber optic communications continue to expand along with the continuing emergence of new fiber optic sensors.

New market areas present opportunities where equivalent sensors do not exist. New sensors, once developed, will most likely have a large impact in these areas. A prime example of this is in the area of fiber optic smart structures (*Claus, 1991; Sirkis, 1994; Udd, 1991b; Udd, 1995b*). Fiber optic sensors are being embedded into or attached to materials (1) during the manufacturing process to enhance process control systems, (2) to augment nondestructive evaluation once parts have been made, (3) to form health and damage assessment systems once parts have been assembled into structures and (4) to enhance control systems. A basic fiber optic smart structure system is shown in Figure 3.48.

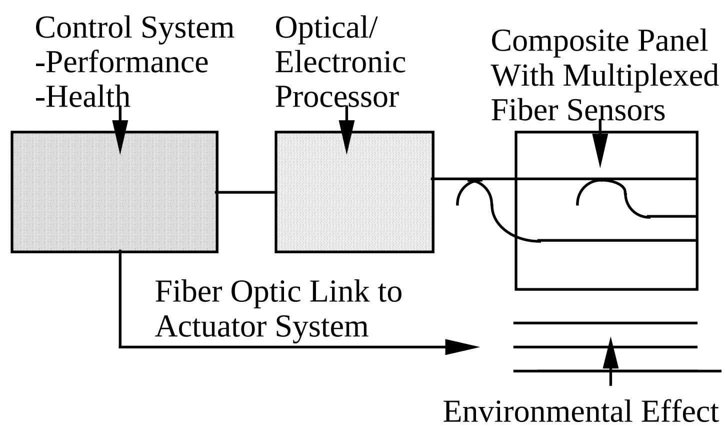


Figure 3.48: Fiber optic smart structure systems consist of optical fiber sensors embedded or attached to parts sensing environmental effects that are multiplexed and directed down. The effects are then sent through an optical fiber to an optical/electronic signal processor that in turn feeds the information to a control system that may or may not act on the information via a fiber link to an actuator.

Fiber optic sensors can be embedded in a panel and multiplexed to minimize the number of leads. The signals from the panel are fed back to an optical/electronic processor for decoding. The information is formatted and transmitted to a control system which could be augmenting performance or assessing health. The control system would then act, via a fiber optic link, to modify the structure in response to the environmental effect.

Figure 3.49 shows how the system might be used in manufacturing. Here fiber sensors are attached to a part to be processed in an autoclave. Sensors could be used to monitor internal temperature, strain, and degree of cure. These measurements could be used to control the autoclaving process, improving yield and the quality of the parts.

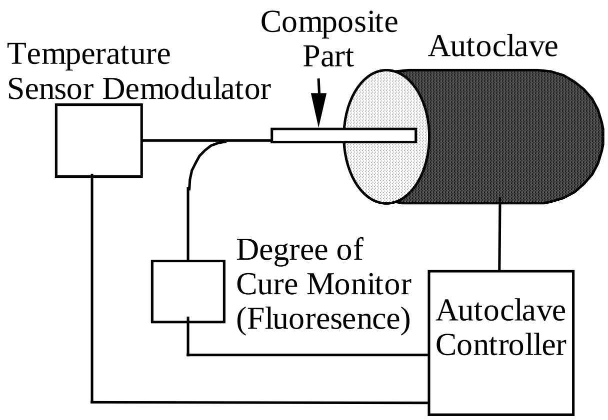


Figure 3.49: Smart manufacturing systems offer the prospect of monitoring key parameters of parts as they are being made, which increases yield and lowers overall costs.

Interesting areas for health and damage assessment systems are on large structures such as buildings, bridges, dams, aircraft and spacecraft. In order to support these types of structures it will be necessary to have very large numbers of sensors that are rapidly reconfigurable and redundant. It will also be necessary to demonstrate the value and cost effectiveness of these systems to the end users.

One approach to this problem is to use fiber sensors that have the potential to be manufactured cheaply in very large quantities while offering superior performance characteristics. Two candidates that are under investigation are the fiber gratings and etalons described in the prior sections. Both offer the advantages of spectrally based sensors and have the prospect of rapid in line manufacture. In the case of the fiber grating, the early demonstration of fiber being written into it as it is being pulled has been especially impressive.

These fiber sensors could be folded into the wavelength and time division multiplexed modular architecture shown in Figure 3.50. Here sensors are multiplexed along fiber strings and an optical switch is used to support the many strings. Potentially the fiber strings could have tens or hundreds of sensors and the optical switches could support a like number of strings. To avoid overloading the system, the output from the sensors could be slowly scanned to determine status in a continuously updated manner.

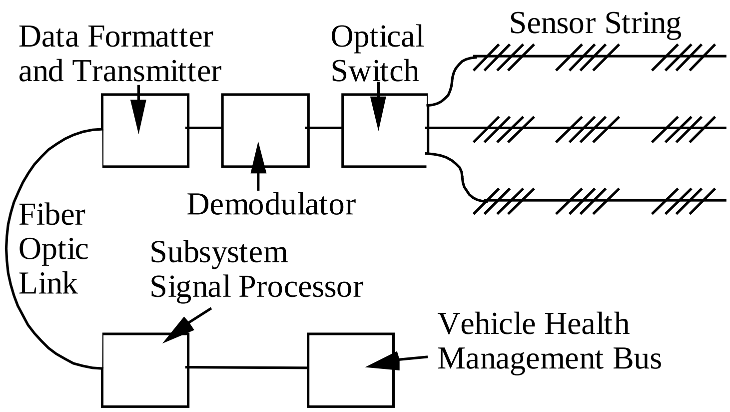


Figure 3.50: A modular architecture for a large smart structure system would consist of strings of fiber sensors accessible via an optical switch and demodulator system that could select key sensors in each string. The information would then be formatted and transmitted after conditioning to a vehicle health management bus.

When an event occurred that required a more detailed assessment the appropriate strings and the sensors in them could be monitored in a high performance mode. The information from these sensors would then be formatted and transmitted via a fiber optic link to a subsystem signal processor before introduction onto a health management bus. In the case of avionics, the system architecture might look like Figure 3.51. The information from the health management bus could be processed and distributed to the pilot or more likely, could reduce his direct workload leaving more time for the necessary control functions.

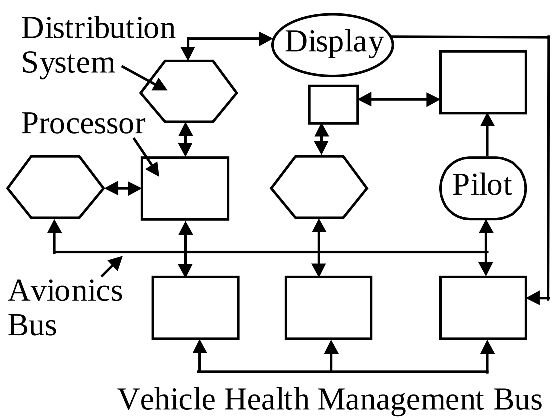


Figure 3.51: A typical vehicle health management bus for an avionics system would be the interface point for the fiber optic smart structure modules of Figure 3.50.

As fiber to the curb and fiber to the home moves closer to reality there is the prospect of merging fiber optic sensor and communication systems into very large systems capable of monitoring the status of buildings, bridges, highways and factories over widely dispersed areas. Functions such as fire, police, maintenance scheduling and emergency response to earthquakes, hurricanes and tornadoes could be readily integrated into very wide area networks of sensors as in Figure 3.52.

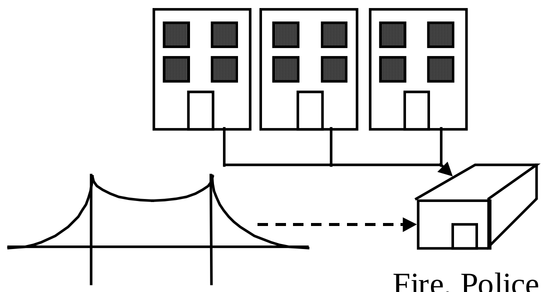


Figure 3.52: Fiber optic sensor networks to monitor the status of widely dispersed assets as buildings, bridges and dams could be used to augment fire, police and maintenance services.

It is also possible to use fiber optic sensors in combination with fiber optic communication links to monitor stress build-up in critical fault locations and volcano dome build-up. These widely dispersed fiber networks may offer the first real means of gathering information necessary to form prediction models for these natural hazards.

4.0 GENERAL INTRODUCTION TO FIBER OPTIC SENSORS FOR TRANSPORTATION INFRASTRUCTURE APPLICATIONS

In the following sections, fiber optic sensors with the potential to be widely used in a variety of transportation infrastructure applications will be described in greater depth.

4.1 MICROBEND SENSORS

4.1.1 Basic Operation

When an optical fiber is deformed, light will leak from the core area into the cladding. If the fiber is arranged so that light coupled into the cladding is stripped out there will be a net intensity change in the propagated light beam as shown in Figure 4.1.

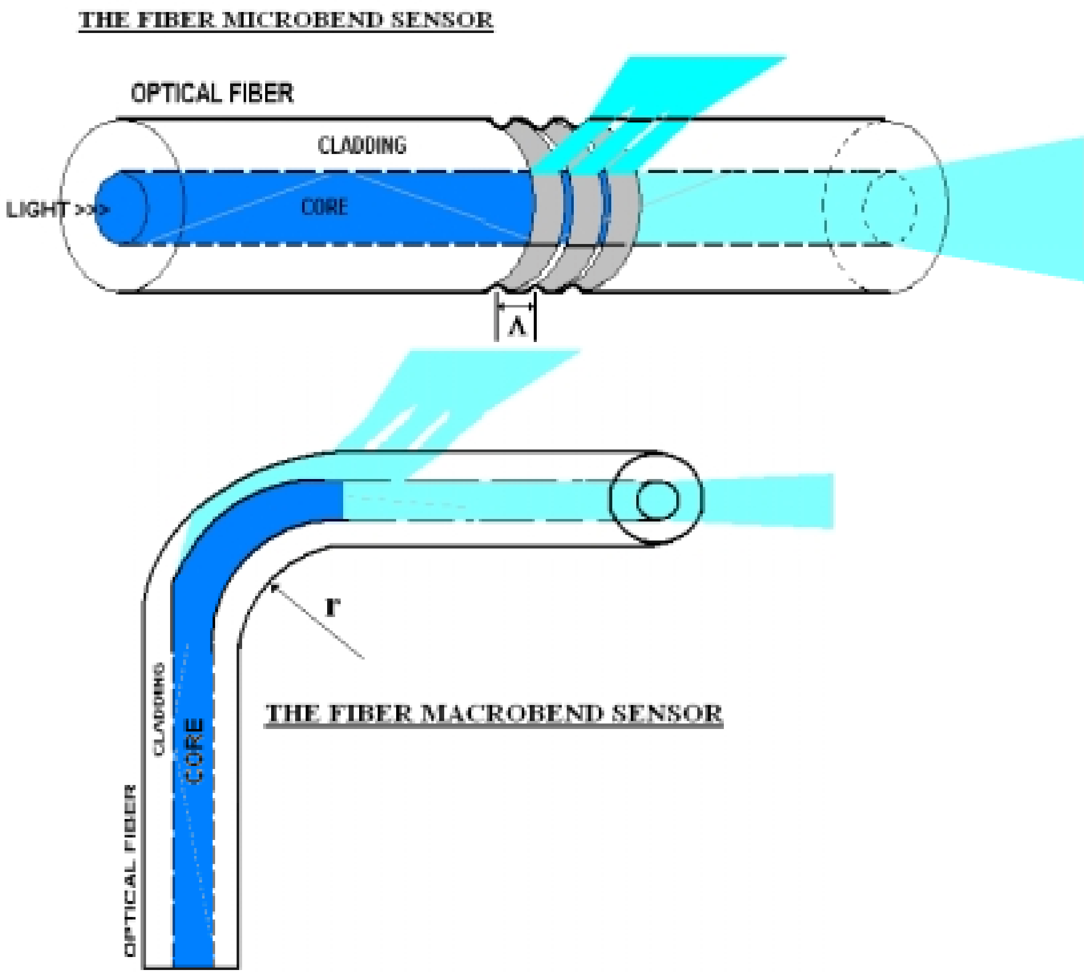


Figure 4.1: Microbend and macrobend loss

In the fiber microbend sensor of Figure 4.1, if step index fiber is used, maximum light will be stripped out of the core when the wavelength of the disturbance or perturbation that causes the microbending, Λ, is:

$$\Lambda = \frac{\pi a}{\sqrt{\Delta}} \tag{4-1}$$

where a is the radius of the fiber core and:

$$\Delta = \frac{n_0^2 - n_{cl}^2}{2n_0^2} \tag{4-2}$$

with n_o being the peak core refractive index and n_{cl} being the index of refraction of the cladding.

The sensitivity to microbending will depend on a number of factors including the numerical aperture, where smaller values indicate the light beam is weakly guided by the core, the number of deformations and how close the period of the perturbation is to Λ.

There are two usual approaches to implementing fiber sensors based on microbending. The first uses an artificially induced mechanical perturbation period. This can be done by spiraling a wire about an optical fiber with a given period, using special coatings that have a periodic structure, or placing the fiber into a structure that is designed with a specific period. Measurements are then made of the remaining light transmitted by the core as a function of the environmental effect to be measured. The second approach is to use a microbend sensitive fiber and place it into a structure that has random or nearly random perturbations. This may result in light loss over a wavelength band.

Both of the above approaches have been used with some success. The accuracy of the system is usually limited to about 3 to 5% due to errors induced by mechanical misalignments of optical components, macrobending losses, variations in the period of the perturbation and wavelength shifts in the system.

In the fiber macrobend sensor of Figure 4.1, the amount of light lost to the cladding is a function of the macrobend radius r.

4.1.2 Applications

Microbend sensor systems are generally used when highly accurate measurements are not required and low cost is of paramount importance.

An example of a commercial product that has been introduced using fixed perturbations is a safety mat placed in front of rotating machinery that disables machines when an operator is at an unsafe location. The microbend sensitive fiber is woven directly into the mats. The company Herga, in the UK, is an example of a supplier of these mats.

A microbend strip sensor might be designed that would withstand the temperatures and pressures encountered during paving with asphalt concrete. It could be put directly under the top mat during construction and take the place of traffic sensing loops that are used for controlling traffic signals. The same strip sensor could also be used to replace failed conventional loops. These applications would prevent the need to saw joints into the pavement for the placement of traditional loops, thereby decreasing pavement problems.

Another commercially available system that detects fires in large buildings or other large areas of coverage, the microbend sensitive fiber, is surrounded by a spiral spring embedded in a wax coating about the fiber. When a fire occurs, the wax melts and the spring causes local microbending that can be used to locate the position of the fire. Erikson, of Sweden, developed this fire detection system.

Demonstrations have been conducted on large civil structures such a pipelines. In this case, microbend sensitive fiber has been placed in a coating that has a periodic perturbation induced in it. The coated fiber is then bonded to the pipeline at joints where strain induces the coating to create local microbending of the fiber. The localized losses can be used to locate excess stress regions.

McDonnell Douglas, using thin composite parts similar to those employed in aircraft has demonstrated microbending systems using random perturbations to measure impact and monitor manufacturing processes and tension. While these demonstrations served to show that qualitative information could be obtained, most aerospace system requirements require higher accuracy.

The microbend sensor shown in Figure 4.2 is the “figure 8”. As the “figure 8” is tightened the losses due to bending increase. Sensors that could estimate up to 30 cm could probably be designed. Large movement sensors such as this could provide critical information about the conditions at expansion joints during seismic events.

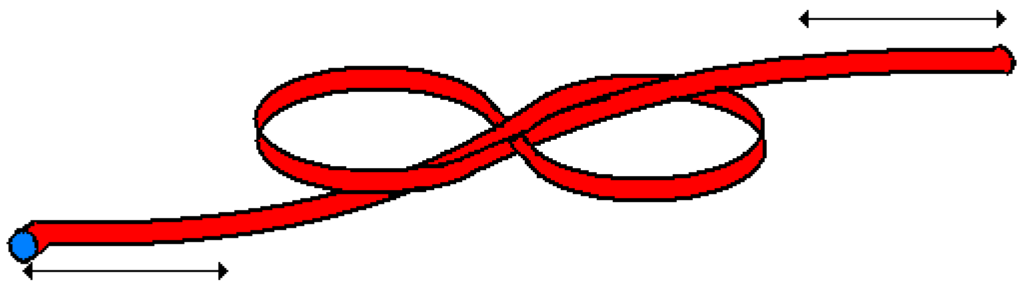


Figure 4.2: “Figure 8” sensor for detecting large movements

4.1.3 Advantages/Disadvantages

The major advantages of microbend sensitive fiber are that the optical fiber is low cost and when used in combination with optical time domain reflectometry techniques they may be used to cover a wide area.

The principal disadvantage of using microbend sensitive fiber is that their overall accuracy is usually rather low. A 95% level of repeatability for a system would be good, but 90% might be more typical.

There are cases where high overall accuracy is not a significant factor such as the presence or absence of someone standing on a mat, a fire being present or not and the location of large strains. In these cases microbend sensors have the potential to be used successfully in commercial applications.

4.2 ETALON SENSORS

4.2.1 Basic Operation

A fiber Fabry-Perot etalon cavity sensor consists of two inline reflective surfaces or mirrors. When these surfaces are formed on facing ends of optical fibers they are referred to as extrinsic fiber etalons. Intrinsic fiber etalons have the reflective surfaces in a single fiber. Figure 4.3 shows a schematic of an etalon with light source and detector. The light transmitted through the etalon (T) is peaks that are spaced out in frequency c/2L in air.

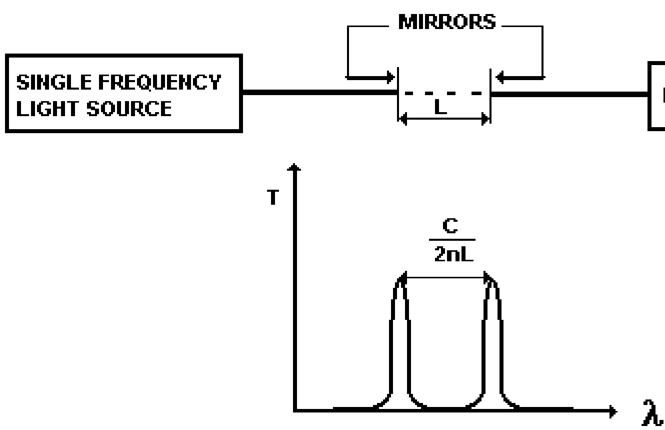


Figure 4.3: The two mirror etalon

These sensors are used to measure strain or temperature. When strain measurements are made in widely varying temperature conditions the temperature must be compensated for by taking an independent temperature measurements or packaging the sensor to be thermally insensitive.

The extrinsic geometry can result in sensors that are very delicate and hard to handle. To overcome this problem, the fibers can be placed in a capillary tube whose internal diameter is on the order of the fiber diameter and spliced in place. This approach results in an etalon that is called the “in-line fiber etalon”, or ILFE. The extrinsic fiber etalon and the ILFE have air gaps between the mirrors, which eliminates birefringence induced by transverse loading. Extrinsic and intrinsic fiber sensor and demodulation systems have been commercialized and are available from Fiber and Sensors Technologies in Blacksberg, Virginia, (703) 552-5128, and by FISO in Quebec, Canada, (418) 652-9885. Blue Road Research has worked closely with Sandia National Labs and Stanford who have evaluated demodulation units from both of these companies. A third company, Fiber Fabry Perot Industries Incorporated located in Bryan, Texas, (409) 775-

2093, uses mirrors that are formed directly into the optical fiber. This is done by cleaving the optical fiber, placing a dielectric mirror of titanium dioxide on the end of the fiber, and then splicing it in place. This approach is more sensitive to errors induced by transverse strain and also requires temperature compensation if nearly static strain measurements are being made.

The intrinsic Fabry-Perot fiber etalon is formed by fusing the two mirrors into the fiber. This process is accomplished by cleaving the optical fiber, placing a dielectric mirror of titanium dioxide on the end of the fiber and then splicing it in place. This approach is more sensitive to errors induced by transverse strain and requires temperature compensation if nearly static strain measurements are being made.

4.2.2 Applications

The extrinsic Fabry-Perot fiber etalon sensors are mainly being used to support single point static strain measurements. They have been used to support experiments on aircraft, to monitor manufacturing processes for structures and bridges, and to measure pressure. Additionally, they can be configured to measure the index of refraction of liquids.

The intrinsic Fabry-Perot fiber etalon sensors are being used principally to support time varying strain measurement applications. This includes measuring strain on vibrating machinery and cylinder heads operating at elevated temperatures, as well as measuring dynamic loads on railway bridges.

4.2.3 Advantages/Disadvantages

The principal advantages of Fabry-Perot fiber etalons are that they have gauge lengths that are similar to conventional strain gauges, are immune to electromagnetic interference, can be made to operate in high temperature environments, and are shock and vibration resistant. They are well suited to applications where dynamic strain, vibration or pressure variations are occurring. Static measurements of longitudinal strain or temperature may also be made effectively.

Their disadvantages include difficulties associated with measuring temperature and strain simultaneously. This is especially important where slowly varying static strains are to be determined over wide temperature excursions. Generally, the commercially available systems do not adequately address this issue, which may be critically important to cases where it is desired to measure the internal strain and temperature in areas of a structure that are difficult or impossible to access without destroying part of the structure.

4.3 GRATING SENSORS

4.3.1 Basic Operation

4.3.1.1 Fiber Grating Fabrication

There are several methods to manufacture fiber gratings. Two of these methods have been demonstrated to meet high temperature performance requirements.

The “holographic” method for writing fiber gratings, which was developed by United Technology, uses two short wavelength laser beams that are side imaged to form an interference pattern through the fiber (*Meltz, 1989*). After a long exposure, ranging from minutes to hours, bright and dark fringes are formed that correspond to an index of refraction modulation of the core of the fiber, which is the fiber grating. These fiber gratings operate up to about 500 degrees C before they start to fade, are characterized by high optical quality and have reflectivities that are over 50%.

Another approach is to produce a fiber grating by side imaging with very intense short duration pulses. Unlike the holographic approach, the index difference appears to be due to optical damage. The temperature at which they operate before fading occurs is about 800 degrees C. The Naval Research Lab has demonstrated that these fiber gratings may be manufactured while the fiber is being drawn, resulting in the potential for very low cost units. However, the optical quality of the fiber gratings is comparatively very low, with a reflectivity of about 2%.

An earlier approach to making fiber gratings based on side imaging of a short wavelength light source using a phase mask, was devised by the Communications Research Lab in Canada (*Hill, 1978*). The light source can be a high intensity UV lamp, in place of a laser. These fiber gratings exhibit high optical quality and temperature performance up to about 500 degrees C. This approach is being widely used by fiber researchers investigating fiber gratings since the equipment needed for fabrication is relatively low in cost.

The Communication Research Lab also pioneered an approach where fiber gratings may be written line by line, resulting in high performance gratings that operate up to about 800 degrees C. The high cost of these fiber gratings may be justified for certain applications.

4.3.1.2 Multiple Axis Strain and Temperature Measurement Using Fiber Gratings

A major issue associated with strain sensors in general is temperature dependence. When accurate strain measurements are to be made in situations where the temperature varies widely and rapidly, such as the manufacturing of composite materials and the in flight performance of aircraft, strain sensors that are either not temperature dependent or are temperature compensated, are required.

One approach is to use a dual overlaid fiber grating, which involves writing two fiber gratings directly over each other, at well-separated wavelengths, such as 1.3 and 1.5 microns (*Udd, 1995a*). The spectral outputs of the overlaid fiber gratings results in two equations in two unknowns, strain and temperature, that can be rapidly processed and solved. This approach has not only been demonstrated, but has been documented in papers that have recently begun to appear in the literature (*Xu, 1994*).

A method of overlaying four fiber gratings, two of which are angled in the direction of the transverse axes, has been devised to solve the problem of off axis strain measurements. Although fiber gratings of this type were produced, demonstrations of transverse sensitivity are not known of. These approaches have McDonnell Douglas patents pending.

The selected approach for this program involves writing two overlaid fiber gratings onto birefringent fiber (*Udd*). The fiber would be polarization preserving fiber with a beat length of about two millimeters. The wavelengths of the fiber gratings are written at 1.300 and 1.550 microns. By writing onto the highly birefringent fiber, four gratings are established. In the case of a two millimeter beat length they would be about 1300.0, 1300.5, 1550.0 and 1550.7 nm. Also because the birefringent axes are well defined, transverse strain can be measured along with longitudinal strain and temperature through four equations in four unknowns. Figure 4.4 illustrates an overlaid fiber grating.

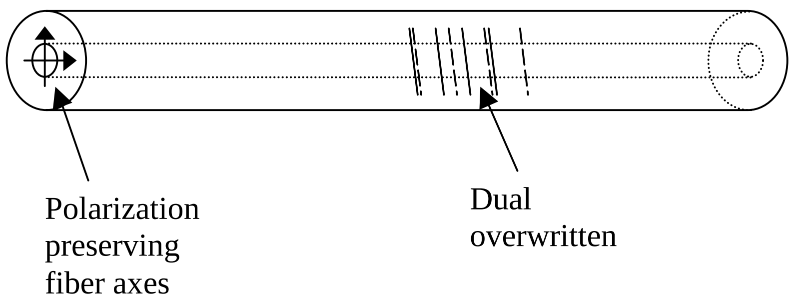


Figure 4.4: Three-axis strain and temperature sensor based on dual overwritten fiber gratings on polarization preserving fiber

4.3.1.3 Fiber Grating Demodulation Methods

One of the key issues in successfully implementing fiber optic grating sensor systems is the method used to extract the spectral content of the signal. Since a 1000 microstrain input corresponds to approximately 1 nm of spectral change, a demodulator capable of resolving 10 microstrain must be able to resolve 0.01 nm. There are many methods that have been proposed including fiber gratings, overcoupled beam-splitters, Fabry-Perot etalons, acoustooptic modulators, interferometers and charge-coupled-device (CCD)/dispersive element approaches.

The fiber grating demodulation system uses a broadband light source, which might be a light emitting diode, that is coupled into an optical fiber and used to illuminate a fiber grating. The returned spectrally modulated signal from the fiber grating is directed by a coupler through a fiber reference grating.

In open loop operation with the two spectral profiles of the sensing and reference fiber grating overlapped, the resulting signal on the detector is predominantly second and even order harmonics. When the signal fiber grating is stretched or compressed, first order harmonics appear whose amplitude is proportional to the compression or extension and whose phase determines direction.

For the closed loop operation, a system would have to be designed to compress and extend the reference fiber grating. Since this is difficult, only open loop implementations of this approach are likely to be commercially viable.

The overcoupled beam-splitter approach uses a broadband filter such as an overcoupled coupler. This approach has been used by Blue Road Research to implement a low cost demodulation system at 1.3 microns and works well for relative strain measurements with a single fiber grating or, using wavelength division multiplexing methods, fiber gratings that are well separated spectrally.

An intrinsic Fabry-Perot etalon based demodulator is available commercially and has been used extensively by Texas A&M for strain measurements.

An extrinsic Fabry-Perot etalon consists of coated or un-coated cleaved fiber ends in a capillary tube. This type of sensor has been used primarily by Virginia Tech and their affiliates. For demodulation, the variable air gap is controlled by a piezoelectric element. This unit is also available commercially from a number of companies including Queensgate Instruments.

The transmission characteristics of etalons depend on the reflectivity and the spacing between the mirrors. Increasing the mirror reflectivity (higher values of the finesse F) increases the sharpness of the transmission lines allowing better resolution of the fiber grating spectral envelope and can approach that of the fiber grating. Air gap adjustment can be used to adjust the tuning range (free spectral range) and sharpness of the transmission peaks. The main advantage of this approach is that it allows for the possibility of wide tuning ranges capable of supporting multiple strain sensors by wavelength division multiplexing. When time division multiplexing techniques are also used, larger numbers of sensors can be supported.

Other methods, such as acoustooptic, interferometric and CCD based demodulators, can be used. The interferometric approach has the advantage of providing extremely high sensitivity while the CCD method offers the possibility of supporting very large numbers of fiber grating sensors.

4.3.2 Applications

Strain measurements with fiber grating sensors have been demonstrated on bridges, aircraft parts, naval vessel parts and utility poles. These demonstrations usually involve comparisons between conventional strain gauges and the fiber optic sensor gages.

Fiber gratings are finding application in communication systems to support wavelength division multiplexing. Telecommunication and cable TV industries are expected to make widespread use of these devices. Use of these devices by large industries will result in mass-produced fiber gratings at significantly reduced cost.

4.3.3 Advantages/Disadvantages

Fiber optic grating sensors offer multiparameter sensing capabilities including transverse and longitudinal strain, pressure and temperature. They are impervious to electromagnetic interference and will perform at high temperatures.

The main disadvantages are their cost and the cost of the demodulation equipment. As the costs of the sensors comes down to competitive levels it is expected that the increased demand for support equipment will follow.

4.4 RESPONSE OF OPTICAL FIBERS

The optical phase delay, ϕ, in radians, of a light passing through a fiber is given by:

$$\phi = knL \tag{4-3}$$

where:

$k = 2\pi/\lambda$, is the optical wavenumber in a vacuum and λ is the wavelength
n is the core index of refraction
L is the physical length of the fiber (nL is the optical wavelength)

When an optical fiber is exposed to environmental perturbations there are two basic mechanisms to produce a change in phase: direct or indirect coupling of strains to the fiber and thermal effects. For the strain case from Equation 4-3:

$$d\phi = kd(nL) = k(ndL + Ldn) = kL\left(n\frac{dL}{L} + dn\right) \tag{4-4}$$

where n dL corresponds to a physical change in length and L dn to changes in the refractive index. It can be shown that the phase response to axial strain is:

$$d\phi = k\varepsilon ndL \tag{4-5}$$

where ε is the strain optic correction factor (ε ~0.78 for silica glass fiber). Thus, phase change and length change are strongly connected.

When temperature response is considered, Equation 4-4 may be written:

$$\frac{d\phi}{dT} = k\left(n\frac{dL}{dT} + L\frac{dn}{dT}\right) = kL\left(\frac{n}{L}\frac{dL}{dT} + \frac{dn}{dT}\right) \tag{4-6}$$

By controlling the jacket geometry and composition, either the strain-temperature term or the refractive index-temperature term can be made to dominate.

Fiber interferometers have been made that will sense acoustic waves, rotation, temperature, electric and magnetic fields, and current. Two of the areas that have received significant study are in acoustic wave sensing and rotation. Rotation sensing will be discussed further with the Sagnac interferometer.

With an acoustic wave there are two principal effects. The length of the fiber will change due to axial strain and the index of refraction will vary. These effects result in a net change in the optical length of the fiber and a phase change $\Delta\phi$ associated with pressure. Equation 4-4 may be written as:

$$\Delta\phi = knL\left(\frac{\Delta L}{L} + \frac{\Delta n}{n}\right) \qquad \textbf{(4-7)}$$

where ΔL is the axial strain, denoted as S_{11}, and Δn is given by:

$$\Delta n = -\left(\frac{n^3}{2}\right)\left[(P_{11} + P_{12})S_{12} - P_{12}S_{11}\right] \qquad \textbf{(4-8)}$$

where S_{12} is the radial strain and, P_{11} and P_{12} are termed “Pockels’ coefficients”.

One of the major research areas in acoustic wave sensing has resulted in the development of the compliant mandrel hydrophone. With careful design of the jacket material and the mandrel, outstanding sensitivity and linearity has been achieved.

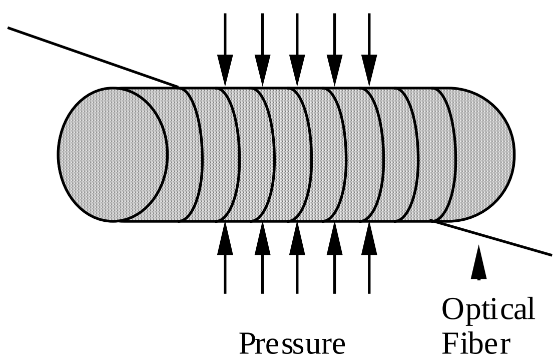


Figure 4.5: Compliant mandrel fiber optic acoustic sensor

4.5 INTERFEROMETRIC SENSORS

4.5.1 Basic Uses

Two-beam interferometry allows measurement of extremely small phase shifts in the optical fiber. Note that, if the differential of Equation 4-3 is taken:

$$\frac{d\phi}{\phi} = \frac{dk}{k} + \frac{dn}{n} + \frac{dL}{L} \qquad \textbf{(4-9)}$$

the n and L terms respond to environmental stimuli while the k term can be used to optimize the measurements of n and L.

4.5.1.1 Mach-Zehnder and Michelson Interferometers

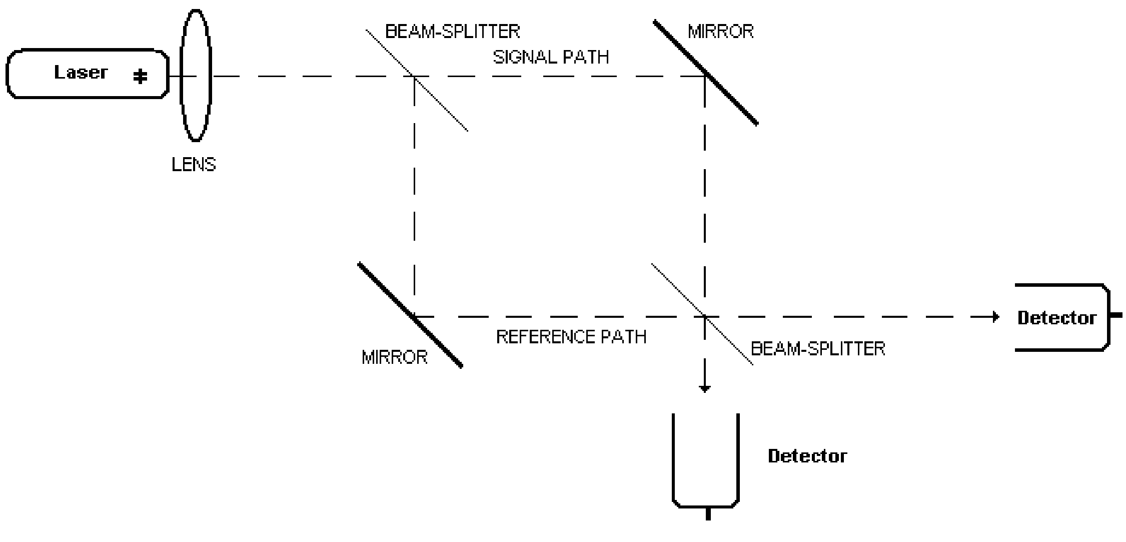


Figure 4.6: Bulk optic Mach-Zehnder interferometer

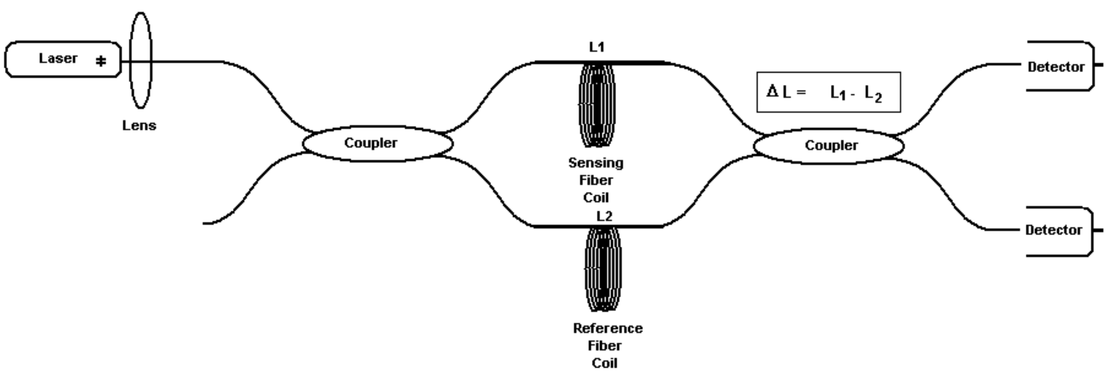


Figure 4.7: Fiber optic Mach-Zehnder interferometer

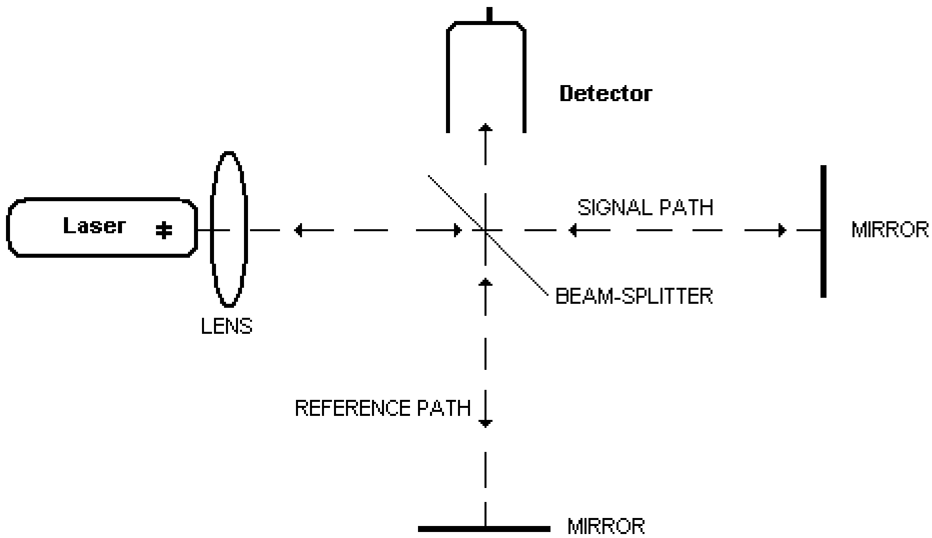


Figure 4.8: Bulk optic Michelson interferometer

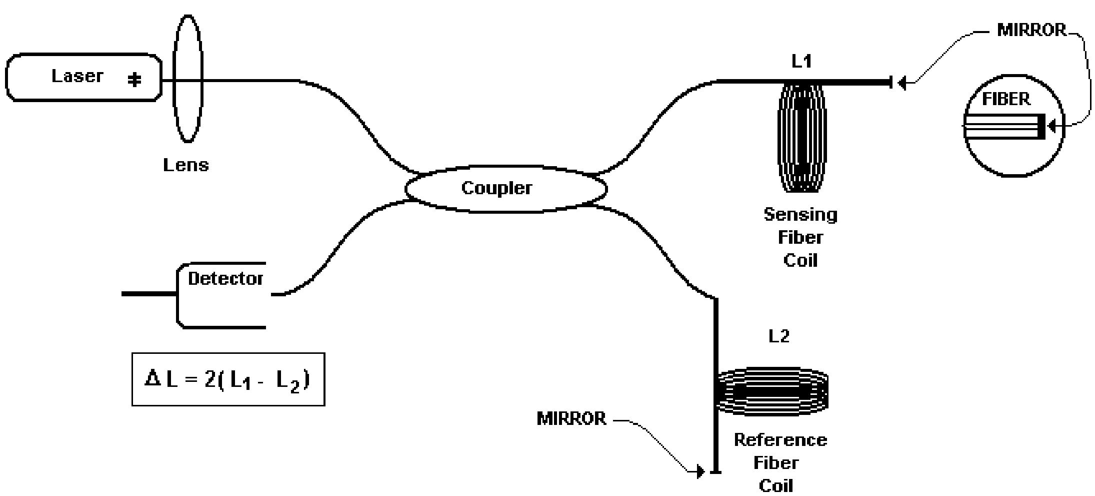


Figure 4.9: Fiber optic Michelson interferometer

These interferometers are usually considered together because of the similarities in geometry. The main difference is the Mach-Zehnder requires two couplers and the Michelson requires reflective ends on the fibers.

Historically these bulk optic interferometers were principally used for:

- width and fine structure of spectrum lines
- length or change in length in terms of wavelengths of light
- determination of refractive index.

The methodology for making these determinations can be seen from Figures 4.6 – 4.9. If the optical path length, nL_1 and nL_2, are the same, the split light beams have the same phase when they recombine since $knL_1 = knL_2$. When the optical path length of the sensing coil changes, the relative phase of the components of the recombined light beam changes, and interference fringes are formed. The visibility of the fringe pattern is defined as:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \qquad \textbf{(4-10)}$$

where I_{max} and I_{min} are the intensities at the maxima and minima of the fringe pattern. For the Michelson interferometer, the change in path length equals the number of fringes counted multiplied by the half wavelength of the light source and nm resolution of length can be realized.

4.5.1.2 The Sagnac Interferometer

The Sagnac interferometer for guidance and control is based on the Sagnac effect, which is experienced in measuring rotation rate. In Figure 4.10, suppose the index of refraction of the optical medium is 1. Clockwise (CW) and counterclockwise (CCW) beams of light propagate in opposite directions in the ring with radius R. The time, Δt, for the CW light to complete one revolution is $2\pi R/c$, where c is the speed of light. Now let the ring rotate in the CW direction at a rate, Ω radians/sec. During the time it took the light to reach the original starting point, the optical path length has increased an amount $R\Omega\Delta t$. The total distance to complete one full revolution in the ring is now $2\pi R + R\Omega\Delta t$. Similarly, the total distance traversed in the ring by the CCW is $2\pi R - R\Omega\Delta t$. Thus, the total optical path length difference is $2R\Omega\Delta t$.

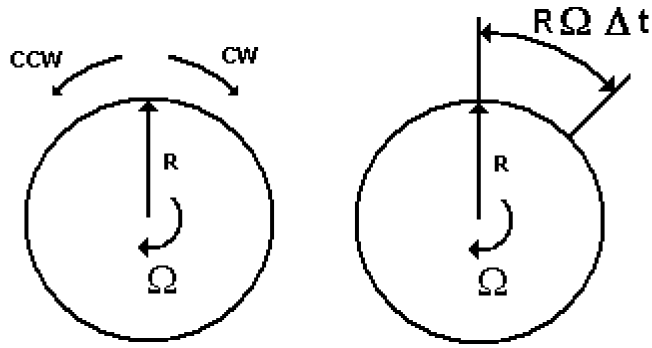


Figure 4.10: The Sagnac effect

Optical resonators require that there be an integral number of waves around an optical circuit as shown in Figure 4.11.

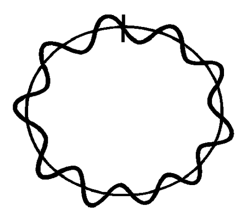


Figure 4.11: Optical resonator

If f is the frequency of the CW wave then:

$$f_{CW}\Delta t = \frac{2\pi R + \Omega R \Delta t}{\lambda} \quad \textbf{(4-11)}$$

And in the CCW direction:

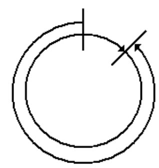
$$f_{CCW}\Delta t = \frac{2\pi R - \Omega R \Delta t}{\lambda} \quad \textbf{(4-12)}$$

Combining these equations gives:

$$f = f_{CW} - f_{CCW} = \frac{2R\Omega}{\lambda} \quad \textbf{(4-13)}$$

which is the characteristic equation for ring laser gyros.

For open loop interferometers, the path length difference (Figure 4.12) divided by the wavelength of light gives the number of fringes produced from the rotation.



$$Z_{\Omega} = \frac{(2\pi R)(2R)}{\lambda c}\Omega$$

Figure 4.12: Open loop interferometer

4.5.1.3 The Sagnac Interferometer as an Acoustic Sensor

The advantages of the Sagnac acoustic sensor for higher frequencies, with respect to the Mach-Zehnder and Michelson interferometers are:

> (1) filtering of lower frequency noise components as the response of the Sagnac acoustic sensor at low frequency is directly proportional to the frequency,
>
> (2) optimum performance is obtained by using a low coherence light source such as a light emitting diode which generally has higher reliability and the ability to withstand higher temperatures than the long coherence length laser light sources required by Mach-Zehnder and Michelson interferometers, and
>
> (3) distributed sensing capability.

One of the major potential advantages of the Sagnac fiber optic acoustic sensor is that there is a rapidly emerging industrial base for this type of interferometer that contrasts markedly with the Mach-Zehnder and Michelson interferometers. Several companies worldwide including Hitachi, JAE, Litton, Honeywell and Andrew Corporation are mass producing fiber optic gyros, with the leader producing approximately 3000 units per month, principally to support the automobile navigation market. Current prices for these units are less than $500 each for 1000 unit buys. These kinds of projected costs and supporting industries allow the prospect of Sagnac acoustic sensors competing effectively with piezoelectically based devices for certain applications.

Disadvantages of the Sagnac fiber optic acoustic sensor include a response that, at low frequencies, is linearly proportional to frequency. Hence the response of this type of sensor at 1000 Hz is a thousand times higher than at 1 Hz. Also the sensitivity of the Sagnac interferometer increases with the square of the length of the Sagnac coil for a given frequency. These disadvantages apply most strongly to applications that require the detection of low frequency signals with high sensitivity.

On balance, the Sagnac fiber optic acoustic sensor may be extremely competitive in certain specific applications where its unique properties of optically filtering of low frequency components of noise, distributed sensing capabilities and environmental ruggedness, are an advantage.

Figure 4.13 is a basic diagram of a Sagnac acoustic sensor. Light is coupled from a source, which could be a light emitting diode, into a single mode optical fiber and split, by a central fiber beam-splitter, into counter-propagating light beams in a fiber coil. When an acoustic wave impinges on a portion of the fiber coil it locally changes the effective optical pathlength. If the acoustic wave is offset from the center of the fiber coil it will generate a net optical pathlength difference between the counterpropagating light beams that will show up as a phase difference between the two light beams when they recombine on the central beamsplitter. If the two light beams are in phase the light will be directed to the light source. If the two light beams are 180 degrees out of phase the light will be directed toward the detector. For intermediate cases the light will be split. In this way the phase difference between the counterpropagating light beams induced by the acoustic wave is converted into an amplitude modulated signal.

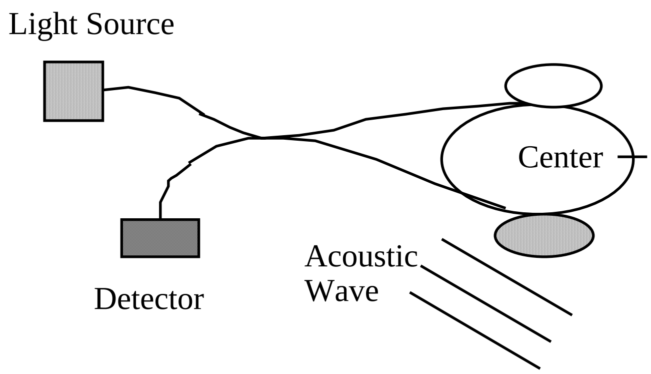


Figure 4.13: Sagnac acoustic sensor

Note also that in the center of the Sagnac loop both counterpropagating light beams arrive at the same time and the result is that when an acoustic wave impinges in this area no net phase shift results. As the acoustic wave moves along one side of the coil, the time delay at this location will be increased as the acoustic wave moves toward the central beamsplitter. Thus, the Sagnac acoustic sensor has a position dependent acoustic response.

Figure 4.14 shows the effect on a Sagnac acoustic sensor of an acoustic wave with a wavelength that is large compared to the Sagnac coil. If the entire coil is unshielded and the acoustic wave essentially acts over the entire coil length, there are equal and opposite phase shift induced on the counterpropagating light beams on each side of the fiber coil.

In Figure 4.14, the vertical axis is placed at the position corresponding to the center of the fiber coil where the net induced phase shift is zero. For the unshielded case the net phase shift between the counterpropagating light beams will be zero. This is the situation where designers of fiber optic gyros seek to minimize the effects of acoustics and vibration on the rotation sensors. The Sagnac acoustic sensor designer on the other hand will usually be seeking optimum sensitivity and will shield portions of the fiber coil and maximize sensitivity of other parts. By shielding half the coil, large net phase shifts may be achieved. Alternatively, one can also use push-pull transducer arrangements so that the net induced phase shift has the same sign.

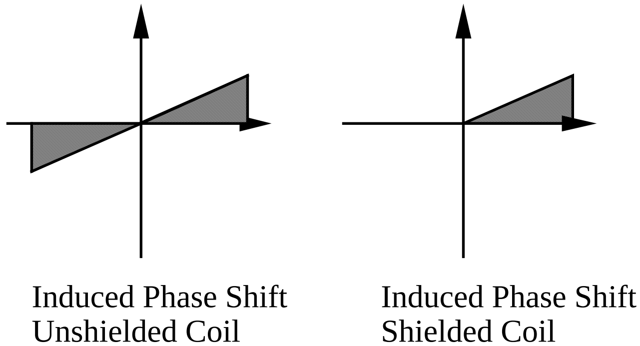


Figure 4.14: Effect of an acoustic wave, which has a wavelength that is large compared to the Sagnac coil on a Sagnac acoustic sensor

Figure 4.15 shows the two most common approaches for shielding the fiber for optimum sensitivity. In one case a portion of the fiber coil is isolated from the acoustic wave by an enclosure. In the second case, a portion of the fiber is coated with a jacket for high acoustic response while the other half is shielded.

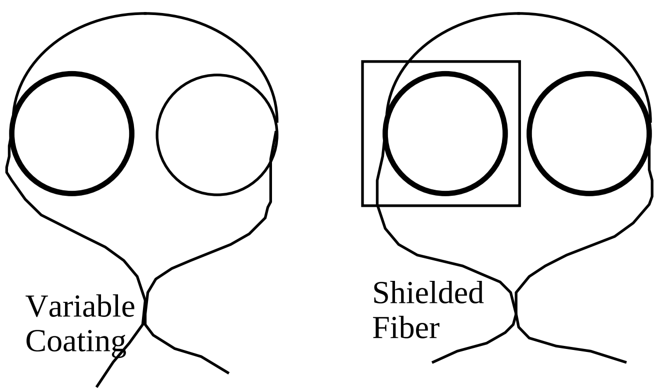


Figure 4.15: Two methods for shielding fiber to obtain optimum sensitivity

In general, the response of the Sagnac fiber optic sensor to a time varying effect such as an acoustic wave can be calculated readily.

In Figure 4.16, clockwise and counterclockwise light beams are circulating about a Sagnac loop. The light beam propagating in the clockwise direction will arrive at the position dy, which is located a distance y from the central beamsplitter in the time yn/c, where n is the index of refraction of the optical fiber and c is the speed of light in a vacuum. The light beam propagating in the counterclockwise direction will arrive at the position dy at the time (L-y) n/c where L is the length of the fiber coil.

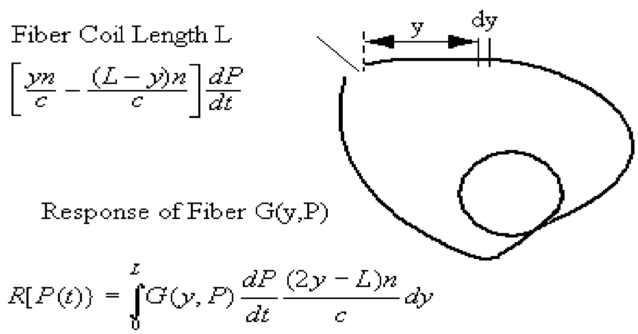


Figure 4.16: Time varying effect

Now suppose that a time varying effect such as an acoustic wave impinges on the fiber coil. If the pressure induced on the coil is P, then the net pressure difference at dy at the time of arrival of the clockwise and counterclockwise light beams is given by:

$$\Delta P = P_{cw} - P_{ccw} = \left[\frac{yn}{c} - \frac{(L-y)n}{c}\right]\frac{dP}{dt} \tag{4-14}$$

The fiber coil response to a pressure P will depend on its position y, as well as factors such as a different jacketing material or shielding on the fiber. If the response of the fiber as a function of position were given by G (y, P), then the net response over the length of the fiber would be (using Equation 4-15):

$$R[P(t)] = \int_0^L \left[G(y,P)\frac{dP}{dt}(2y-L)\frac{n}{c}\right]dy \tag{4-15}$$

It is interesting to look at Equation 4-15 for specific cases. When:

$$G\ (y, P) = A = constant,$$

then R[P(t)] = 0, this is the case when the response of the fiber coil is uniform over the entire length of the coil, a desirable condition.

Graphically it corresponds to the unshielded coil case shown in Figure 4.14. When:

$$G\ (y, P) = A = constant\ for\ L/2 < y < L$$

and:

$$G\ (y, P) = 0\ for\ 0 < y < L/2$$

then Equation 4.14 takes the form:

$$R\left[P(t)\right]=\left[\frac{AnL^{2}}{4c}\right]\frac{dP}{dt} \qquad \textbf{(4-16)}$$

If we assume a sinusoidal pressure wave such as:

$$P(t) = B\sin(\omega t) \qquad \textbf{(4-17)}$$

where B is a constant, then Equation 4-16 becomes:

$$R\left[P(t)\right]=\frac{ABnL^{2}}{4c}\omega\cos(\omega t) \qquad \textbf{(4-18)}$$

There are a number of very interesting features to Equation 4-18, including the sensitivity of the Sagnac fiber optic acoustic sensor increasing as the square of the fiber coil length L and the response of the sensor being proportional to ω. The analysis above is only valid for frequencies ω that are low compared to the fundamental loop frequency given by c/2Ln. Still the analysis provides insight into the ability of the Sagnac interferometer based acoustic sensor to act as an optical filter that may be used to reduce undesired noise effects.

4.5.2 Advantages of Interferometric Fiber Sensors

Advantages of these sensors include extremely high sensitivity, wide area distribution, the ability to be multiplexed in large numbers and combinations of interferometric sensors that allow the measurement of the location and amplitude of time varying events. The mass production of fiber optic gyros over the past few years offers the prospect that key interferometric components will continue to drop in price enabling cost-effective systems.

5.0 SYNTHESIS OF SENSOR APPLICATIONS

5.1 MICROBEND SENSORS

5.1.1 Current Research

Research on bend loss induced fiber sensors is directed toward displacement measurements (*Sinkiewicz*, *1996*), and load (*Coussignac*, *1996*) and strain (*Schaefer*, *1996*) measurements. The displacement sensor consists of an optical fiber that is tied in a figure eight loop, as shown in Figure 5.1.

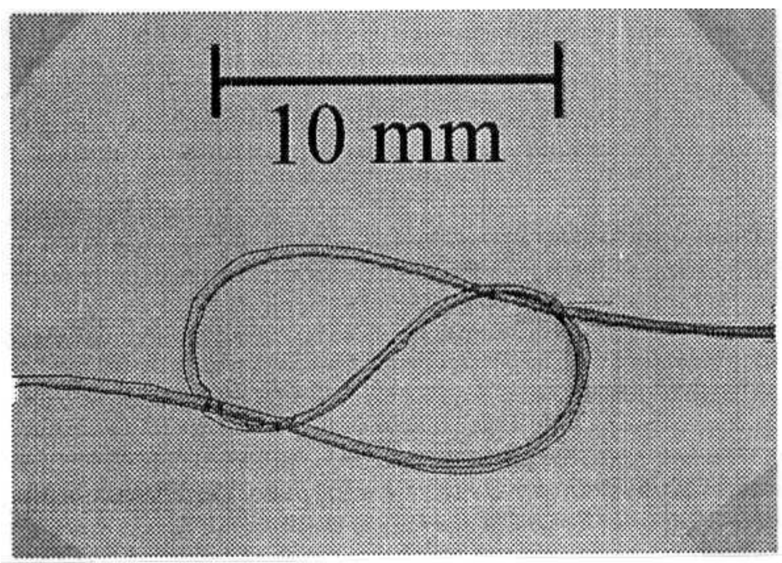


Figure 5.1: Bend loss induced displacement sensor

Displacement of the fiber, which is indicated by the light loss, decreases the loop radius. Figure 5.2 shows an experimental set-up to test this sensor, consisting of a light source and a detector to measure relative throughput.

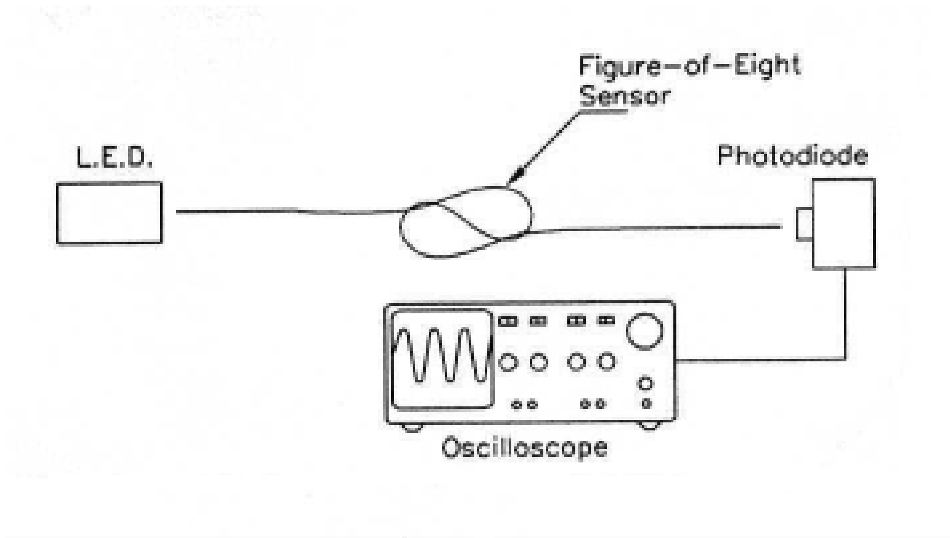


Figure 5.2: Basic setup to support bend induced displacement sensor

The sensor output is reasonably linear over a range of about 20-mm, as is shown in Figure 5.3. It could be potentially used for displacements of perhaps 300 mm, as shown in Figure 5.4, provided curve fitting was used. This simple sensor might be of use in areas where approximate displacement measurements are needed at very low cost. There are issues associated with temperature sensitivity, aging of the coating and long-term performance, which would have to be addressed in a fielded unit.

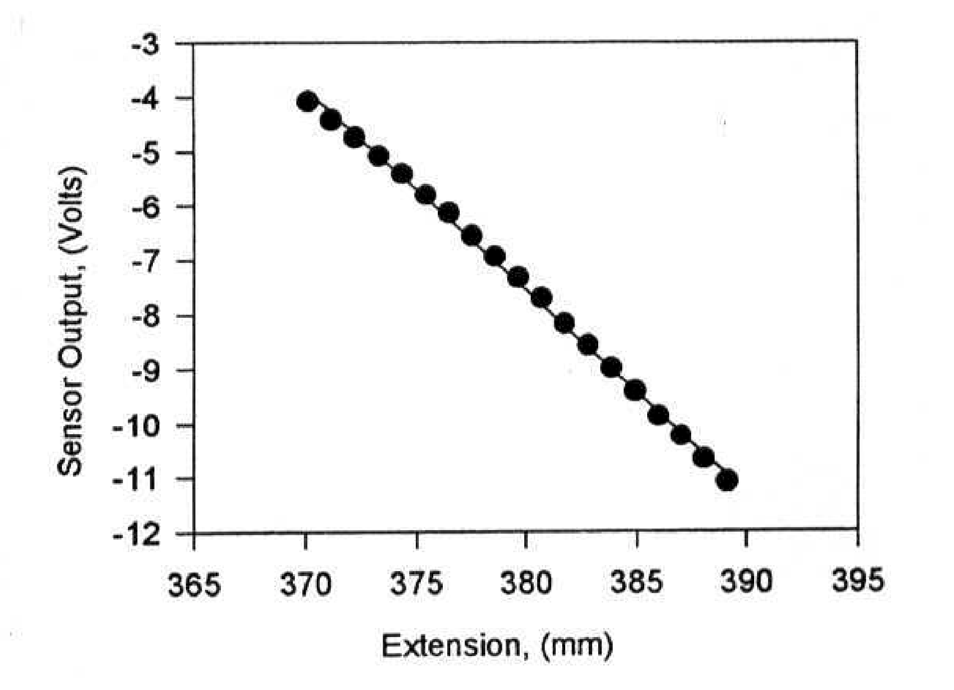


Figure 5.3: Plot of the reasonably linear (~20mm) region of the displacement sensor

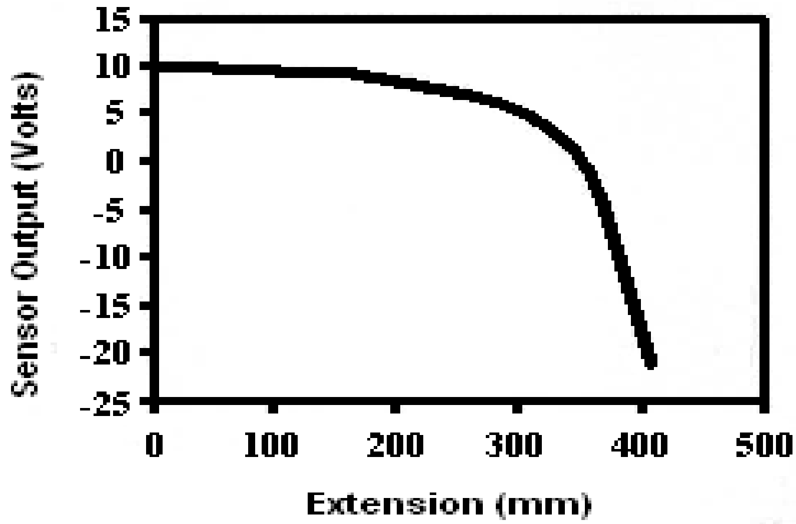


Figure 5.4: Output of the displacement sensor over a 400-mm range

Microbending sensors for instrumented bearing applications are shown in Figure 5.5. Compression is applied to a series of elastomer sheets reinforced by steel plates. This plate in turn induces local microbending that can be used to measure load. By using several sensors, the distribution of transverse load and measurements of shear stress can be made. Figure 5.6 shows the layout of a typical element. V grooves are used to position the sensitive elements across the load cell plate. Figure 5.7 shows the results of loading one of these bearing elements. The hysteresis is typical of microbend sensitive elements with residual microbending loss after an initial loading. The accuracy of perhaps 5 to 10% is also typical of these kinds of devices. Figure 5.8 shows a coil of bend sensitive fiber that has been placed into a patch that is to be used as a strain sensor. When the patch is strained, locally induced microbending results in higher loss through the patch and a measurement of strain.

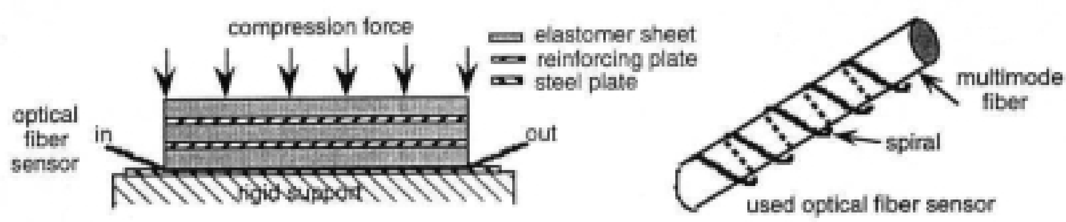


Figure 5.5: Microbend sensitive fiber wound around a mandrel subject to load

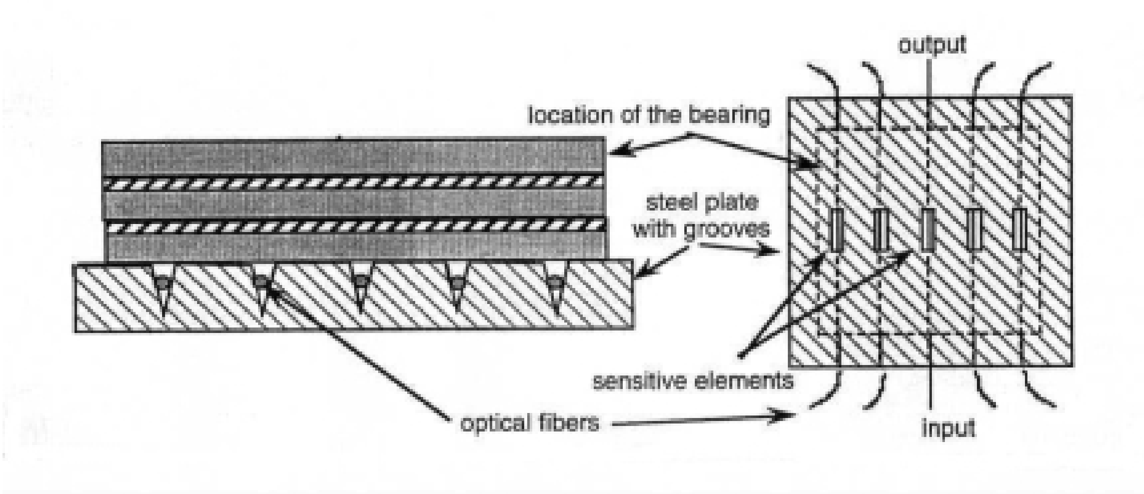


Figure 5.6: Scheme for measuring transverse load using several microbend sensitive elements

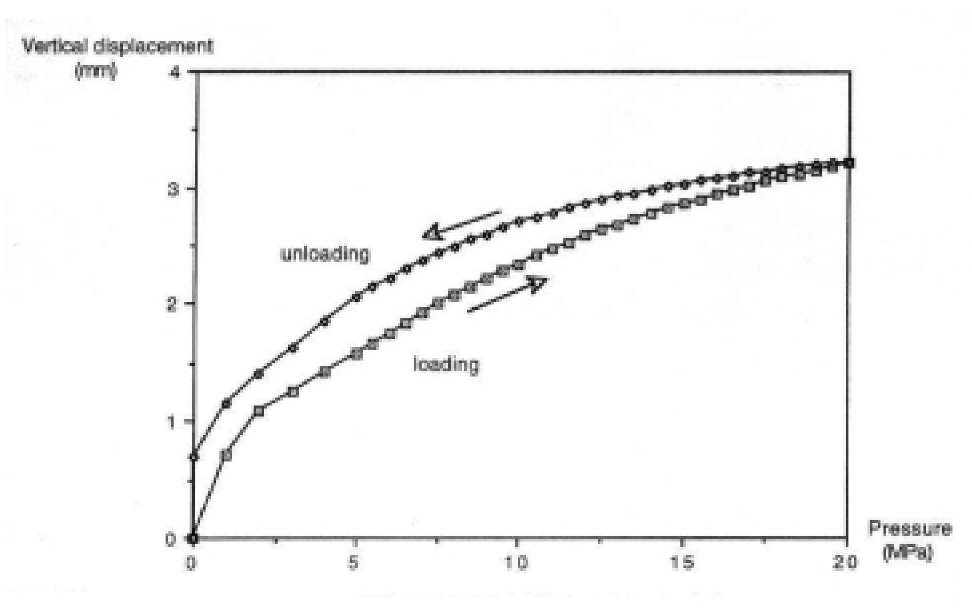


Figure 5.7: Compression load test of the system in Figure 5.6

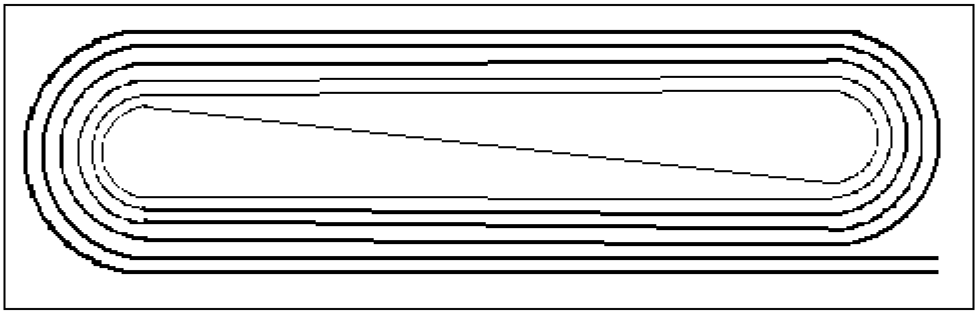


Figure 5.8: Fiber optic strain sensor based on bending loss

5.1.2 Field Applications

Field testing on bend sensitive fiber is historically rather limited. This deficiency is at least in part due to the rather large measurement errors that are present under ambient conditions. If the environment in which the sensors are placed fluctuates widely in temperature, the problems are likely to be severe. As an example, Figure 5.9 shows the sensor of Figure 5.8 attached to a composite pipe which is subject to loading.

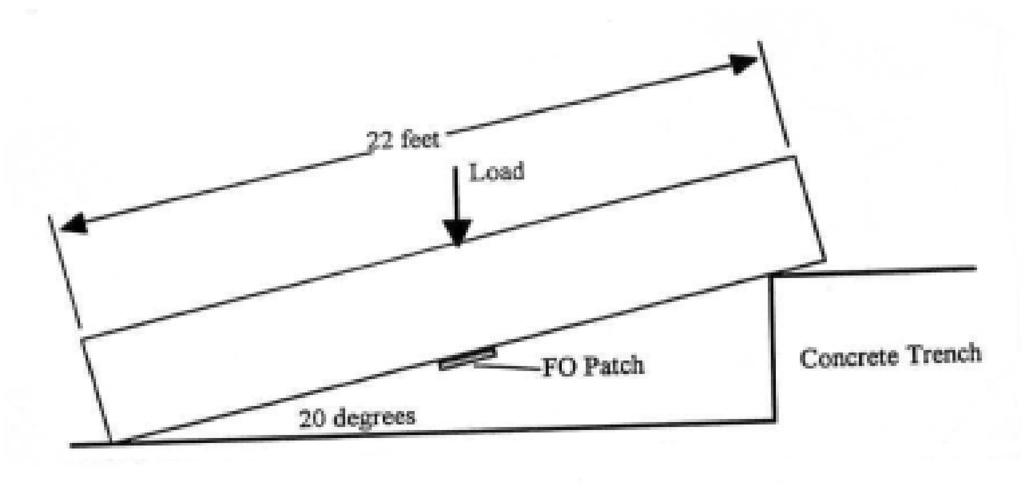


Figure 5.9: Loading of a composite pipe using the sensor of Figure 5.8

The results are shown in Figure 5.10. The tests were conducted at room temperature and are likely to have been substantially worse under widely ranging temperature conditions.

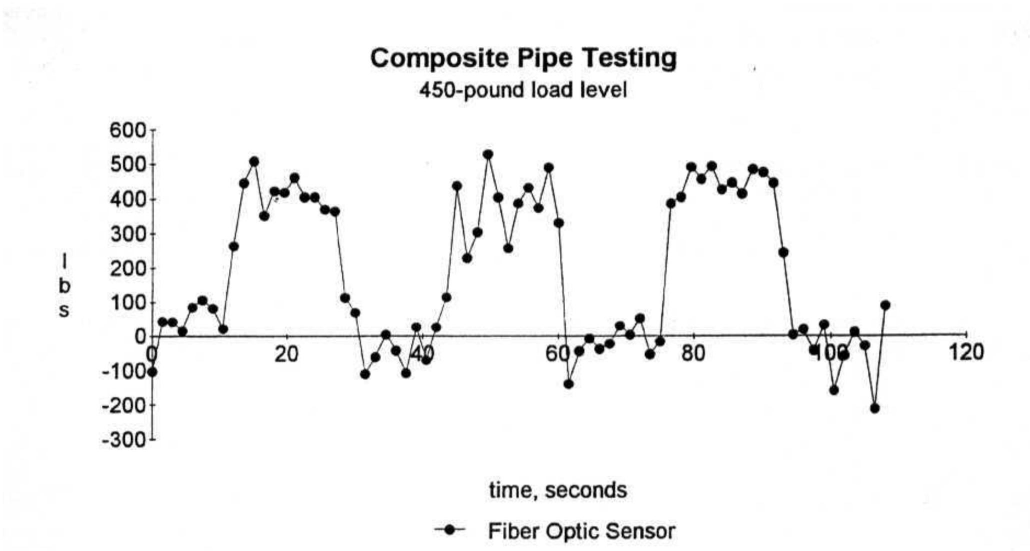


Figure 5.10: Composite pipe load tests using the sensor of Figure 5.8

Examples of successful applications where overall accuracy is not of paramount importance are a pedestrian bridge in Germany (*Huston, 1994*), and safety mats into which microbend sensitive fiber is interwoven to detect the presence or absence of a machine operator (*Dakin, 1995*). Microbend sensitive fibers have also been used for damage assessment in a series of experimental aerospace demonstration structures (*Clark, 1995; Udd, 1991b*).

5.1.3 Installation Details

For many materials, microbending may be induced by the random bending caused by the structure in which the microbend sensitive fiber is embedded. As an example in composite materials, the reinforcing fibers in the composite structure act as natural bend loss sites for the optical fiber. In addition, the microbend sensitive optical fiber can be jacketed in such a way that periodic microbending is induced. When the jacketed fiber is loaded, the overall effect is an increase in loss. As an alternate example, microbend sensitive fiber could be placed and cemented into a groove in a concrete pedestrian bridge.

5.1.4 Component Cost and Availability

Microbend sensitive optical fiber is commercially available. Although many types of optical fiber are microbend sensitive, major manufacturers concentrate on telecommunication grade fiber, which minimizes microbend sensitivity. The net result has been that optimized microbend sensitive fiber has become somewhat of a specialty item and the cost is higher than regular telecommunication grade fiber. In very small quantities, it can be a few dollars per meter as opposed to a few cents per meter for telecommunication grade optical fiber.

For very a simple microbend based system demodulator, costs are quite low, involving a moderately controlled light source and detection circuits. Most units that are qualified for field use are based on optical time domain reflectometry, when broad area distributed sensing is to be implemented. Generally, costs and complexity of the devices scale up rapidly if accuracy higher than the 5 to 10% level is desired.

5.1.5 Future Development

Microbend sensors have and are likely to continue to be used in those applications where low cost is of paramount importance and accuracy and repeatability requirements are low. Examples of successful commercial ventures include pressure sensitive cable made by Herga Ltd. and Bury St. Edmunds in the UK, based on microbending and a series of bend sensitive fiber optic sensors made by Measurand, Inc. in Fredericton, New Brunswick, Canada.

5.2 ETALON SENSORS

5.2.1 Current Research

Fiber etalons are primarily being used to support strain and pressure measurement applications. Most of the research on civil structure applications has been accomplished using the extrinsic Fabry-Perot interferometer, where two reflective fiber ends are placed in a capillary tube separated by an air gap. Such a sensor has been utilized to support the measurement of strains in soil (*Miller, 1996*). The results of this effort indicate that viscoelastic strains in soil may be effectively measured although the data was not definitive with respect to the ability to measure permanent deformation of the soil. A laboratory evaluation of cracking in pavement using extrinsic fiber optic etalons has been analyzed (*Abdel-Mooty*). Under this study a series of fiber optic sensors were embedded and shown to be effective in measuring pavement reinforcement material properties. The fiber sensors were shown to produce measurements that were similar to foil strain gauges. Although the fiber sensors performed well throughout the study, the foil strain gauges were much less effective, with a significant number failing before or during the tests.

5.2.2 Field Applications

Measuring strain in concrete walls during hydration was examined using fiber optic etalon based sensors (*Habel, 1994*). In this case, an extrinsic fiber etalon was installed in a new sewage treatment works facility with reinforced concrete walls. Temperature was controlled in the walls during hydration in order to minimize stress. The extrinsic fiber etalon was embedded into a cement mortar brick with small ears protruding to couple to the surrounding concrete. To avoid loss of absolute calibration in this configuration, a back-up power supply was used to continuously run the demodulator. The system was designed for one microstrain sensitivity, which is beyond the capability of foil gauges. The tests were conducted for 6 days and further details of this field study are expected in later papers. A second field application was performed, where fiber etalons were preset for spacing between the two reflective end mirrors so that sensitivity to strain was maximized (*Krushwitz, 1992*). Some of these sensors were embedded in small sample specimens and the two sides of the fiber etalon attached to small washers to couple to the concrete. These were embedded across a crack in the undersurface of a road while others were bonded with two-part epoxy. A truck was driven on the road, with the fiber etalons measuring strain distribution.

5.2.3 Installation Details

Two means of installation were used in the field tests described in the prior section. In the first case the sensor is embedded into a sample, which might be cement mortar, with metal attachments placed on each side of the etalon for coupling to concrete or asphalt. In the second case, the fiber sensor was bonded to the pavement with two-part epoxy.

5.2.4 Component Cost and Availability

For general pricing information at the time of this report, the following information is offered. Demodulator units are approximately $12,000 to $15,000 each and the individual sensors are approximately $300 each. A basic demodulator unit sells for around $9000 and its sensors are about $150 to $200 each. A 14-channel unit sells for a price of less than $20,000. Individual sensors are in the range of $300 to $500 depending on the type and how they are packaged. In particular, the etalons are sometimes embedded into stainless steel tubes using aluminum to cast the sensor in place. There are two vendors of fiber etalon based devices in the United States and one in Canada; Fiber and Sensors Technologies, Fiber Fabry Perot Interferometers Inc and FISO.

5.2.5 Future Development

There is relatively little study of fiber optic etalons for strain measurements in civil structures, probably due to the potential of fiber optic grating sensors. Fiber optic grating sensors offer a series of important advantages with respect to the etalon including lower potential sensor costs, very straightforward multiplexing capability, the ability to do multiparameter sensing and a great deal of synergy with the telecommunication and cable TV markets. Fiber etalons however do have important applications for vibration and acoustic sensing and it may be that future civil structure applications will take advantage of these capabilities.

5.3 GRATING SENSORS

5.3.1 Current Research

Of the fiber sensors currently being used for measuring strain, fiber gratings are the subject of the most intensive interest. For civil structure applications, this is true as well. This is driven partly by the prospect of very low cost due to synergistic efforts in the telecommunication industry but also by performance advantages that include straightforward wavelength division multiplexing options and gauge lengths that are similar to widely used foil gauges. Several laboratory research activities have been undertaken for fiber grating sensors in civil structures. The usage of fiber gratings in composite wrapped concrete cylinders has been demonstrated (*Davies, 1996*). In this case, fiber gratings were embedded into composites wrapped around the cylinders to improve overall failure strength. In one case compressive strain up to 3.8% was measured. The optical fiber is generally stronger in compression, with tension strain proof tests up to 0.5 to 1% being more common. It is possible to commercially fabricate fiber gratings with strengths that are similar to the original fiber and in special cases up to 2 to 3% tension. A series of tests using small and large-scale structures in the laboratory to look for artificial flaws in parts has been accomplished (*Kodindouma, 1996a*). The fiber gratings when adequately embedded in the concrete structure were able to detect the onset of failure at the steel-concrete interface and monitor data up to failure. The usage of fiber grating sensors on a full-scale laboratory bridge have been reported, as well (*Kodindouma, 1996b*). In this case 48 fiber grating sensors and 49 resistive foil gauges were used to monitor the bridge with locations chosen by using finite element analysis. Tests were performed using a scanning etalon demodulator with the sensors subject to static strain. The usage of fiber grating sensors in a 22-foot composite utility to measure strain and compression was also demonstrated (*Udd, 1995c*). In this case, a high speed, potentially very low cost fiber grating demodulation approach, based on an overcoupled coupler, was used. Four fiber grating sensors were used, with two below and two above the lower joint of the pole which was made in three, 3 foot sections. Compression and tension measurements were made as the fiber grating sensor system performed through failure of the pole. All four fiber grating sensors, which survived from the embedding process into the fiberglass pole, through all the tests to pole failure, were used to measure compression induced by the manufacturing process. Also, fiber gratings in other cylindrical composite structures including a carbon epoxy missile body, were used (*Udd, 1997*). In this case, a fiber etalon demodulation system was used. Comparisons were made between fiber grating sensors and etalon foil gauges and the two sensors were found to be in very close agreement.

5.3.2 Field Applications

In 1993, the city of Calgary commissioned a bridge that used carbon fiber composite prestressing tendons. These tendons were instrumented with fiber gratings (*Measures, 1994*). Of the 18 fiber gratings installed, 15 survived and functioned properly. A 980 nm light source was used to pump sections of erbium doped fiber essentially allowing the fiber grating sensor to cause lasing. This approach is a very expensive way to operate fiber grating sensors and requires the usage of extremely low loss angle polished physical contact connectors. However it does provide a strong signal and in this case the primary objective was performance rather than cost.

5.3.3 Installation Details

In both the Calgary bridge installation (*Measures, 1994)* and testing of the carbon epoxy missile body (*Udd, 1997*) conventional strain gauge technology was applied. The procedure in this case involved using conventional strain gauge cements and carefully routing the optical fiber along protected paths to the demodulator. In the case of the Calgary bridge this involved routing the fiber to a junction box at which a connector was terminated. The techniques will be described more fully in another section discussing general installation of fiber sensors into composites.

5.3.4 Component Cost and Availability

Single element fiber gratings range from about $150 to $500 dependent largely on the manufacturer. For a 1000 unit buy, a quote of $50 per fiber grating is reasonable. Discussions with manufacturers of fiber gratings project the cost to drop to the $25 to $40 range in approximately two years. Intrinsic costs of the fiber gratings are quite low and it is expected that in the next five-year period they will become competitive with conventional foil gauges in terms of cost. At the time of this report, there were four companies offering fiber grating demodulation systems; Research International in Woodinville, Washington, Electrophotonics in Toronto, Canada, Micron Optics of Atlanta, Georgia, and Blue Road Research.

5.3.5 Future Development

Fiber optic grating sensors have a wide range of potential uses in civil structures and traffic control. When used as strain sensors, fiber Bragg grating (FBG) sensors can measure axial strain, transverse strain, or both. In some cases, FBG sensors can also be used as acoustic sensors to track anomalies in roads, bridges, railways, etc. by monitoring irregular sounds caused by potholes, excessive vibration, etc. Lastly, FBG sensors can be used to measure temperature, where needed. Next follows a description of the various parts involved in a fiber sensor system, some possibilities for monitoring civil structures and as traffic control aides.

In a typical installation, FBG sensors require a lightsource, a demodulation system, and fiber optic patch cords to connect the sensor. The lightsource and demodulation system can often be packaged together in one box, and connected to a junction box via fiber optic cable (see Figure 5.11)

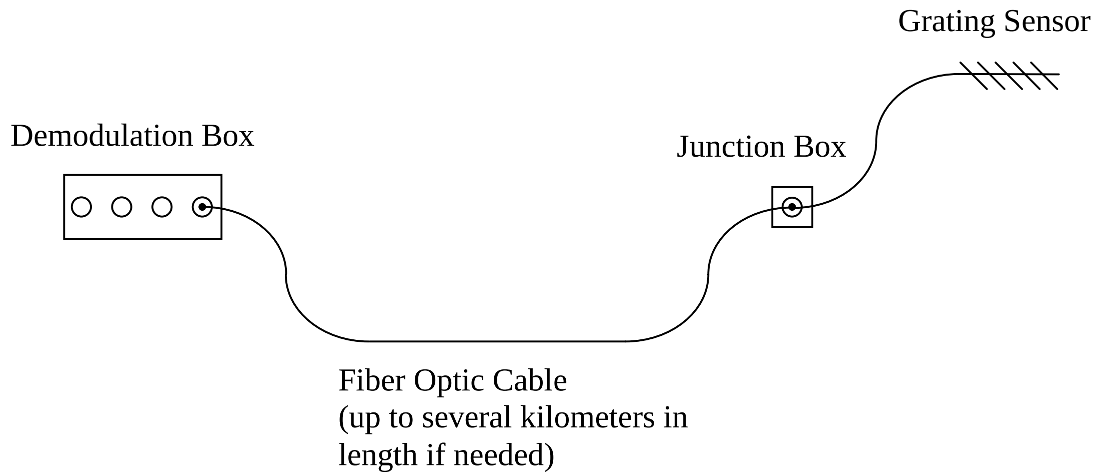


Figure 5.11: Fiber grating sensor demodulation system

Because the FBG sensor is passive, the only point of the system requiring electrical power is the demodulation box, which can be several kilometers from the sensor. The demodulation box could potentially handle more than one sensor, allowing for a more efficient system. The purpose of the junction box is to isolate the sensor from the fiber optic cable in the event that the cable is cut or broken. In this case, the cable could be replaced at a much lower cost than having an expert re-splice the sensor. Field applications for civil structures using this type of system are discussed in Chapter 1.0 of this report.

5.4 INTERFEROMETRIC SENSORS

5.4.1 Current Research

A multiplexed Michelson interferometer in combination with coherence multiplexing to measure strain at multiple locations in bridges and tunnels has been studied (*Inaudi, 1996; Vurpillot, 1996*). Polarimeteric interferometric fiber sensors (*Teral, 1992*) have been used to perform vehicle weigh in motion studies. Combinations of interferometric sensors and fiber grating sensors (*Udd, 1996a*) have been proposed for usage on bridges and other large civil structures to do multifunction distributed sensing to locate damage using both dynamic and static sensing.

5.4.2 Field Applications

The Michelson interferometer system has been installed on a series of bridges and a tunnel in Switzerland. The sensor has a resolution of about 10 microns for a range of gauge lengths that can be many meters long with compensating fiber lengths. The basic instrument has a measurement range of up to 150 mm. Each measurement takes about 10 seconds. As an example (*Vurpillot, 1996*), a bridge near Lausanne, Switzerland was instrumented with 30 fiber optic deformation sensors, as well as foil strain gauges and thermocouples to test the system.

5.4.3 Installation Details

The bridge in Lausanne used fiber sensor leads that were placed in plastic tubing to protect them from the concrete. One sensor lead left loose in the plastic tube measured temperature via thermal expansion of the glass. The second sensor lead was attached via flanges on the fiber optic connectors to the bridge structure and preloaded under strain. When the bridge structure expands or contracts the relative motion of the fiber strain sensors are recorded. Out of the sensing region, the fiber leads are protected in a loose tubing structure and routed to an output junction box.

5.4.4 Component Cost and Availability

Each Michelson interferometer sensor in a plastic tube for mounting costs between $500 and $1000 dependent on the exact configuration used. The demodulation system is about $35,000. The Sagnac distributed sensor is not currently available commercially although it is the subject of investigations by researchers in the United States and South Africa.

5.4.5 Future Development

The Michelson interferometer based system is being deployed on bridges and tunnels in Europe and there is considerable interest there in applying this technology to more structures. The polarization interferometric sensor does not seem to be competitive with fiber grating based systems and for strain sensing and relatively little work seems to be going on in this area. The Sagnac distributed sensor may be used to support very long gauge length sensing and may be used in the future for roads, bridges, tunnels and mines. This sensor requires further development.

5.5 OTHER FIBER SENSORS USED FOR CIVIL STRUCTURES

Fiber optic sensors are being developed in Universities to detect chloride. These chloride detectors have potential application to roadways and bridges (*Fuhr, 1996*). This sensor is designed to be embedded into the rebar-concrete highway and uses a fiber sensor that consists of a reagent at the end of an optical fiber. Light propagating down the fiber causes the reagent to fluoresce and spectroscopic analysis is used to measure chlorine content. A second approach being developed uses a silver chromate strip that changes color upon exposure to chloride, changing the overall transmission efficiency of an optical fiber system (*Cosentino, 1995*). The intensity changes are the basis for measuring chloride content.

Another fiber optic sensor used for civil structures is a fiber optic distributed temperature sensor based on Raman scattering (*Orrell, 1992; Hitachi, 1993*). This fiber sensor allows the measurement of temperature over distance of up to 10 km with an accuracy of about 1-degree C. A two-kilometer unit with accuracy of about 1 degree C sells for about $50,000 while the 10 km unit is approximately $200,000. Although, the exact specifications of this system are currently unknown, the principal of operation is Brillioun scattering.

5.6 SMART STRUCTURES

The effort with respect to fiber optic smart structures (*Udd, 1996b; Udd, 1995b*) for civil applications has largely been directed toward implementation of fiber optic sensing systems for damage and health assessment. Eventually fiber optic cables/communication systems could be used in combination with the sensing systems and an actuator could be used to form active smart structures that react to their environment. In the civil structures case this could mean readjusting tension or other parameters in a bridge or building to react more effectively to an earthquake or excess loading.

5.7 SUMMARY

Fiber optic sensors that have been largely developed in response to aerospace applications are beginning to be used in civil structures. A few installations based on fiber gratings and Michelson interferometer based fiber sensors are being used in the field. To date all of the bridge applications have been accomplished during the construction of the new structure.

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APPENDIX A

INSTALLATION TECHNIQUES FOR FIBER OPTIC SENSORS

Many of the general procedures for installation and protection of sensors also apply to fiber optic sensors. The largest concerns are proper surface preparation, mechanical bonding, and providing protection for the sensor and leads. The intent of this document is to characterize the special handling requirements for fiber optic sensors. Surface preparation procedures (such as those proposed in the Measurements Group, Inc. instruction bulletin *B-129-7, Surface Preparation for Strain Gauge Bonding*, or *TT-611, Strain Gauge Installations for Concrete Structures*) should be employed with the relevant exceptions for handling fiber cables and fiber based sensors. Although emphasis in these documents is on strain gauges, the information is relevant to most sensors.

Fiber optic strain sensors may be surface mounted anywhere an electrical strain gauge may be used. Fiber sensors can also be easily embedded into composite materials without significantly impacting the variable to be measured or causing material weakness. Electrical sensors do not embed easily in materials and can cause structural defects.

SURFACE PREPARATION

The importance of cleanliness for the bonding surface as well as the sensor and fiber can not be over-stressed. Contaminants can decrease the performance of the sensor and possibly shorten the useful lifetime of the sensor. All surfaces must be cleaned and properly prepared for reliable sensor performance. Five main steps are involved in getting a surface ready for bonding the sensor to an existing structure: degreasing, abrading, application of gauge layout lines, conditioning, and neutralizing.

Degreasing

The first step should always be to remove any oils, grease, or chemically soluble contaminants. Many methods and solvents are available depending on the specific materials involved. Always follow the recommended safety and handling instructions provided with any solvent.

Abrading

The surface must be free of any loosely attached materials (such as paint, rust, etc.) that could be a cause of sensing error. In addition, abrasion makes a surface texture suitable for bonding. This step may also include filling of porous materials to maximize bonding area.

Application of Gauge Layout Lines

Accurate placement of the gauge requires location of where the measurement is specifically required. Burnishing lines also help to locate the sensor after installation. Protective coatings are often applied to sensors, obscuring their exact location, and these placement lines become invaluable tools for accurate measurements later.

Conditioning

An acid is used to help further clean the area.

Neutralizing

The conditioning step uses acids that must be safely neutralized so that the bonding adhesives will have the proper pH.

BONDING

Some of the same adhesives used for installing electrical strain gauges can be used for fiber optic gauges as well.

Adhesive Selection

The adhesive chosen will necessarily be driven by the application and materials involved. The same adhesives used to mount foil gauges seem to work very well for fiber optics also. Care must be taken to insure that the adhesive will work for the required lifetime of the sensor. Please follow the manufacturer recommended handling and safety instructions.

Fiber Jacket Removal

Some fiber sensors may have a plastic jacket or protective coating over the sensor. This coating must be removed to insure that strain is mechanically transferred to the sensor. By using special stripping tools or chemicals, the jacket can be removed, or stripped, from the sensor. Special polyamide coated sensors are available that do not require stripping. Since the jacket has properties that allow for efficient strain transference, the sensors may be directly installed.

Clamping

It is helpful to remember that optical fiber is fabricated from glass. Although seemingly very flexible and strong, glass fibers will not survive strong or excessive clamping. Use soft clamping surfaces, applying lesser pressure only when necessary.

Termination of Bare Fiber End

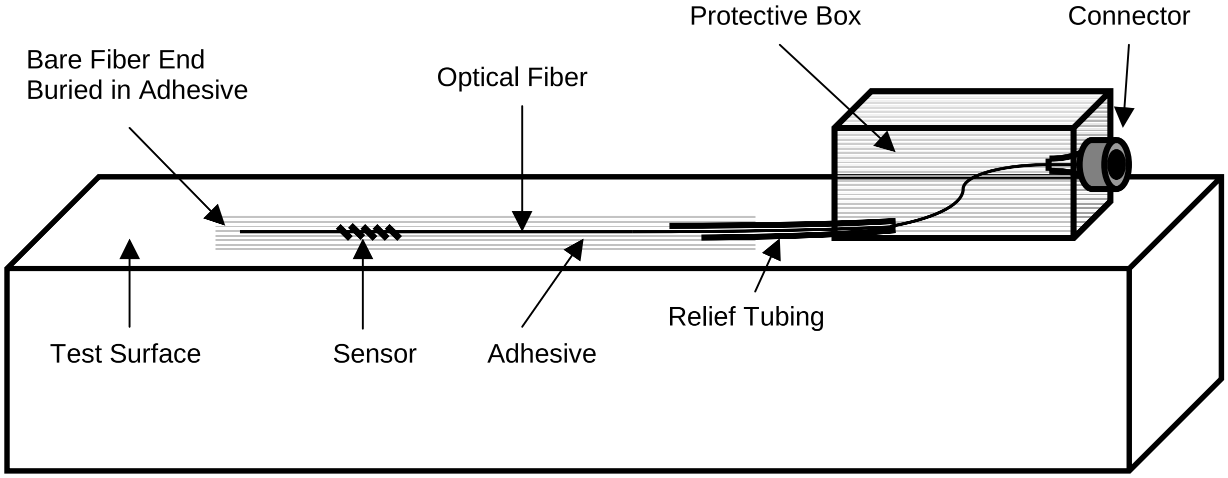
One source of noise in fiber sensors is the back-reflection at air/glass interfaces such as the non-connectorized end of the fiber sensor. The simplest method to reduce this noise is to make certain that the end is buried in the adhesive. It turns out that a glass/adhesive interface will have very little back-reflection.

PROTECTION

Once the fiber sensor is bonded to a surface, care must be taken to protect the area, in order to allow operation of the sensor for the expected serviceable life.

Fiber Strain Relief

A fiber embedded in any material, including epoxy, will tend to break where the fiber comes out of the material. To reduce this possibility, a special protective tube is slid over the fiber before curing as shown in the next figure. This reinforces the fiber at the critical junction; helping to insure the fiber survives.



A protective tube and box are recommended for each installed sensor

Connector Mounting and Protection

It is recommended that the connector be mounted in a protective box similar to what is shown in the figure above. The box allows for easy connection of a cable to the sensor and helps to protect the lead on the fiber sensor from wear and tear.

Clean Connections

Fiber optic connectors are precision optical devices and require special handling. Please refer to Appendix B for the recommended cleaning procedures for connectors.

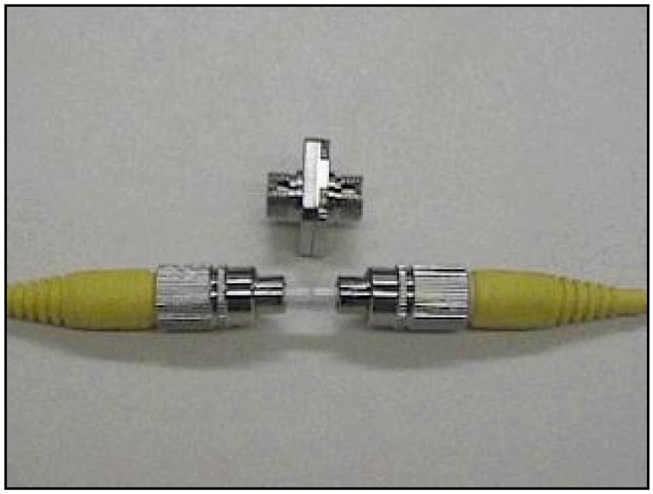
Coatings or Housings

Damage to the sensor, fiber leads, or cable will degrade performance, often to the point of failure. Reasonable protection must be available to all parts of the system. Some suggestions include installing a connector junction box as explained above, overcoating the sensor and exposed fiber with a protective tough coating after installation, running cable and fiber through conduit, weatherizing and placing warning labels near the area. The extent of protection for the fiber sensor and fiber cable should reflect the environmental extremes the system will need to weather, as well as the possibility of damage during construction and maintenance operations.

APPENDIX B

PROCEDURE FOR CLEANING CONNECTORS

In order to ensure proper working condition of all components it is essential to clean each connection end before any new connection is made. The FC connectors supplied on patch cords and modules are designed for precision contact between two flat surfaces. The figure below shows how the connectors look inside the sleeve.



Connectors touch inside of mating sleeve

A dust particle could damage the ceramic surface causing reduced throughput. This tight tolerance requires that each connector remain as clean as possible to insure proper coupling from one fiber to the other.

The recommended method for cleaning fiber connectors is to obtain an Automatic Connector Cleaner (available from mail order fiber optic supply retailers) and follow the manufacturer's directions. An example of such a cleaner is shown in the figure below.

An automatic connector cleaner

Unfortunately, such a cleaner is not always available. An alternative cleaning procedure is presented here for those times when the preferred method is unavailable.

ALTERNATIVE CONNECTOR CLEANING PROCEDURE

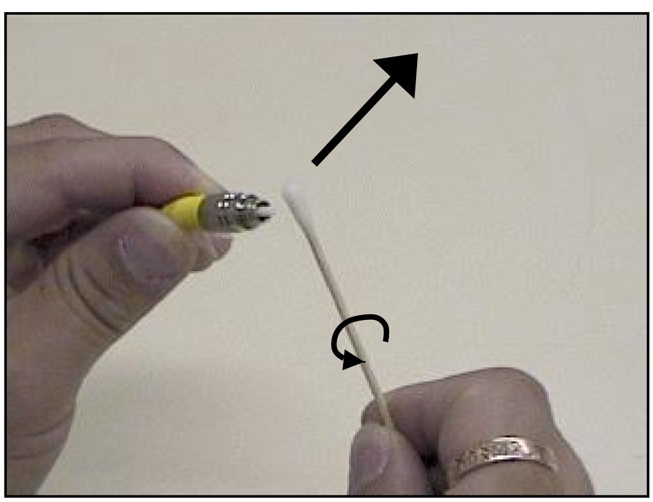
STEP 1:

Place two drops of isopropyl alcohol onto a new pharmaceutical grade cotton cleaning swab as shown in the figure below.

Place two drops of isopropyl alcohol onto a new swab

STEP 2:

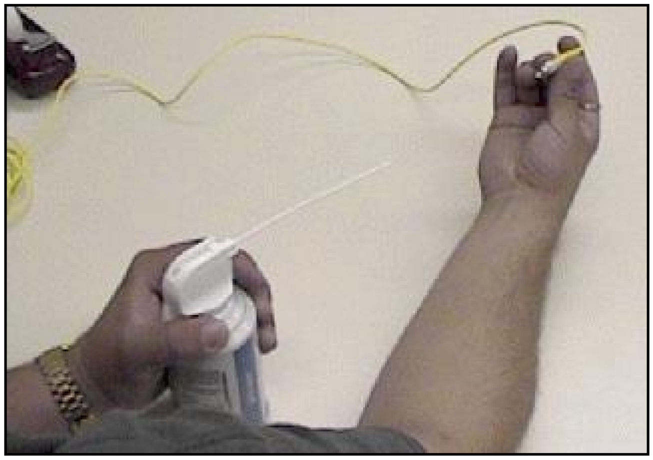
While rolling the swab between thumb and forefinger smoothly roll the swab across the fiber end. The figure below shows the proper motion. Use each swab only once. If the tip still has contaminants on it, repeat this step with a fresh swab.



Roll the swab counter-clockwise while smoothly rolling the swab across the connector tip

STEP 3:

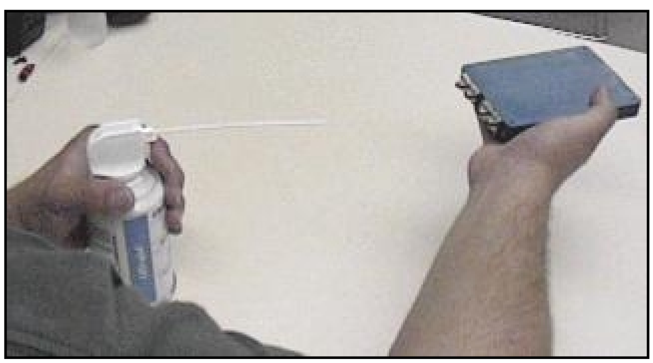
Being careful not to tip the aerosol can (tipping may expel contaminants), blow the connector tip off with a few short bursts of clean air. The figure below shows the proper approximate distance to maintain between the connector and air can.



Blow approximately 10 – 15 cm away from the connector

STEP 4:

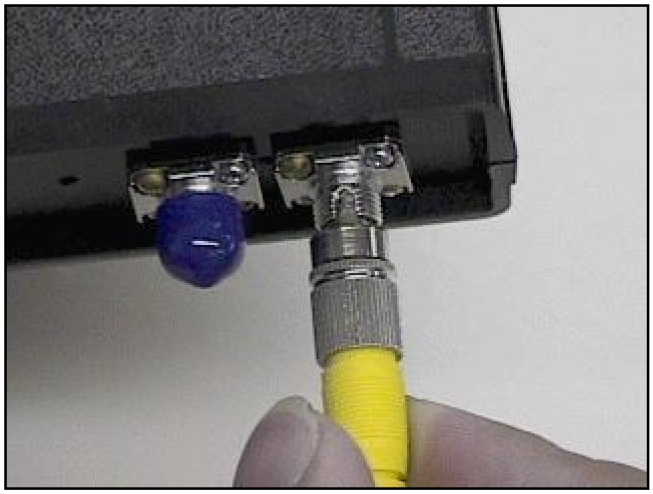
Blow out the connection sleeves to insure no hidden dust remains, as in the figure below.



Always blow out mating sleeves before connection

STEP 5:

The last step is to install the connector in the sleeve making sure the key matches the slot, as shown in the figure below. Screw the connector down finger-tight. Excess force is not needed and may damage the connectors.



Match the key and tighten until just snug